PAUL SCHERRER INSTITUT PSI

muEDM:
The search for a muon EDM using the frozen-spin technique at PSI

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on behalf of the PSI muEDM collaboration

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Outline

- Physics motivation and current status
- Reminder about Fermilab and J-PARC approaches
- Frozen-spin approach at PSI
  - Principle of the measurement
  - Current status
  - muEDM collaboration
- Summary and outlook

Physics Motivation for EDMs

Why are EDMs interesting to measure?

- A search for new physics which is "background-free"
  - The contribution from SM's CKM matrix is too small ($d_e \sim 10^{-44}$ e cm)
- Many BSM models predict large EDMs
  - Complementary to LHC searches
- Matter-antimatter asymmetry requires more CPV
  - EDMs are good probes of BSM CPV

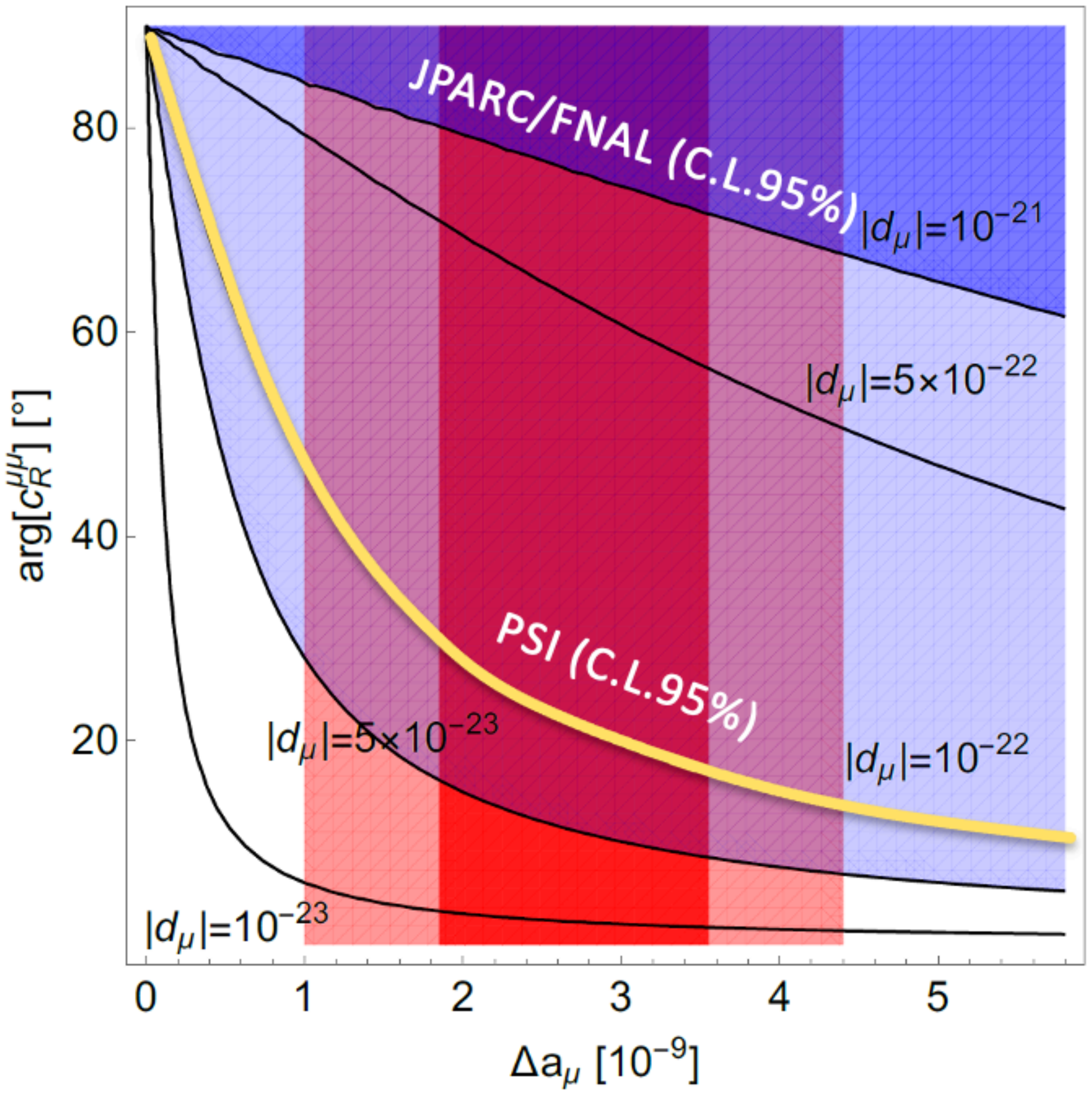
- In some BSM models, muon g-2 and EDM are connected!
  - Once the muon g-2 discrepancy is confirmed, the corresponding signal may show up in the muon EDM searches

Current status for muon EDM

- Standard Model prediction
  - CKM contribution: $d_\mu^{CKM} \sim 10^{-42}\ \mathrm{e \cdot cm}$ PRD 89 (2014) 056006
- Experimental bounds
  - Muon: $d_\mu^{EXP} < 1.8 \times 10^{-19}\ \mathrm{e \cdot cm}\ (95\,\%\ \mathrm{C.L.})$ BNL Muon (g-2) collaboration, PRD 80 (2009) 052008
  - Electron: $d_e^{EXP} < 1.1 \times 10^{-29}\ \mathrm{e \cdot cm}\ (90\,\%\ \mathrm{C.L.})$ ACME collab., Nature 562 (2018) 355
- Indirect bounds
  - Minimal flavor violation: $|d_\mu| = \dfrac{m_\mu}{m_e}|d_e| < 2.3 \times 10^{-27}\ \mathrm{e \cdot cm}$ PLB 500 (2001) 161; NPB 645 (2002) 155; JHEP 08 (2014) 019
  - Decoupled e-μ sector (EFT): $|d_\mu| < 0.9 \times 10^{-20}\ \mathrm{e \cdot cm}$ PRD 98 (2018) 113002
  - EDMs of heavy atoms: $|d_\mu| < 2 \times 10^{-20}\ \mathrm{e \cdot cm}$ PRL 128 (2022) 131803

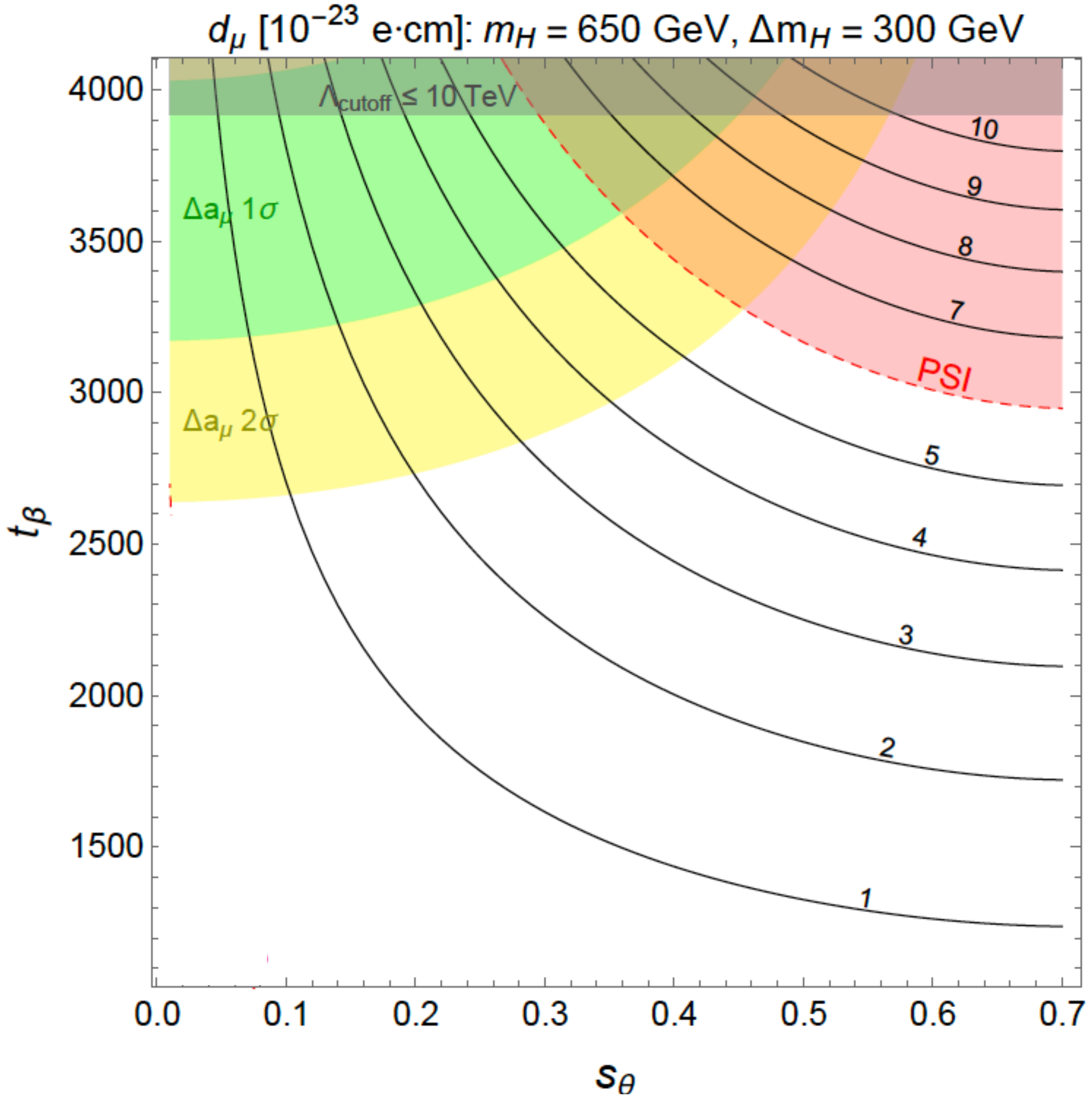
BSM/EFT models with large EDM

EFT Analysis



PRD 98 (2018) 113002

Muon specific 2HDM

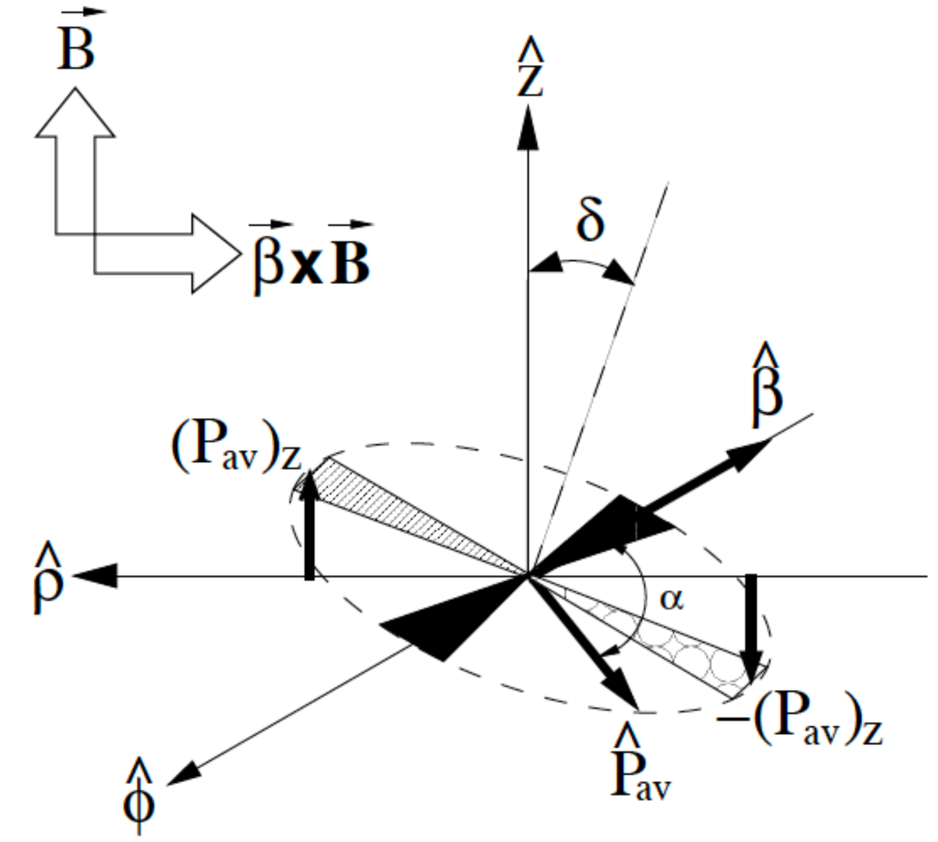


Interesting parameter space: $s_\theta \sim 0.35$, tanβ ~ 3700

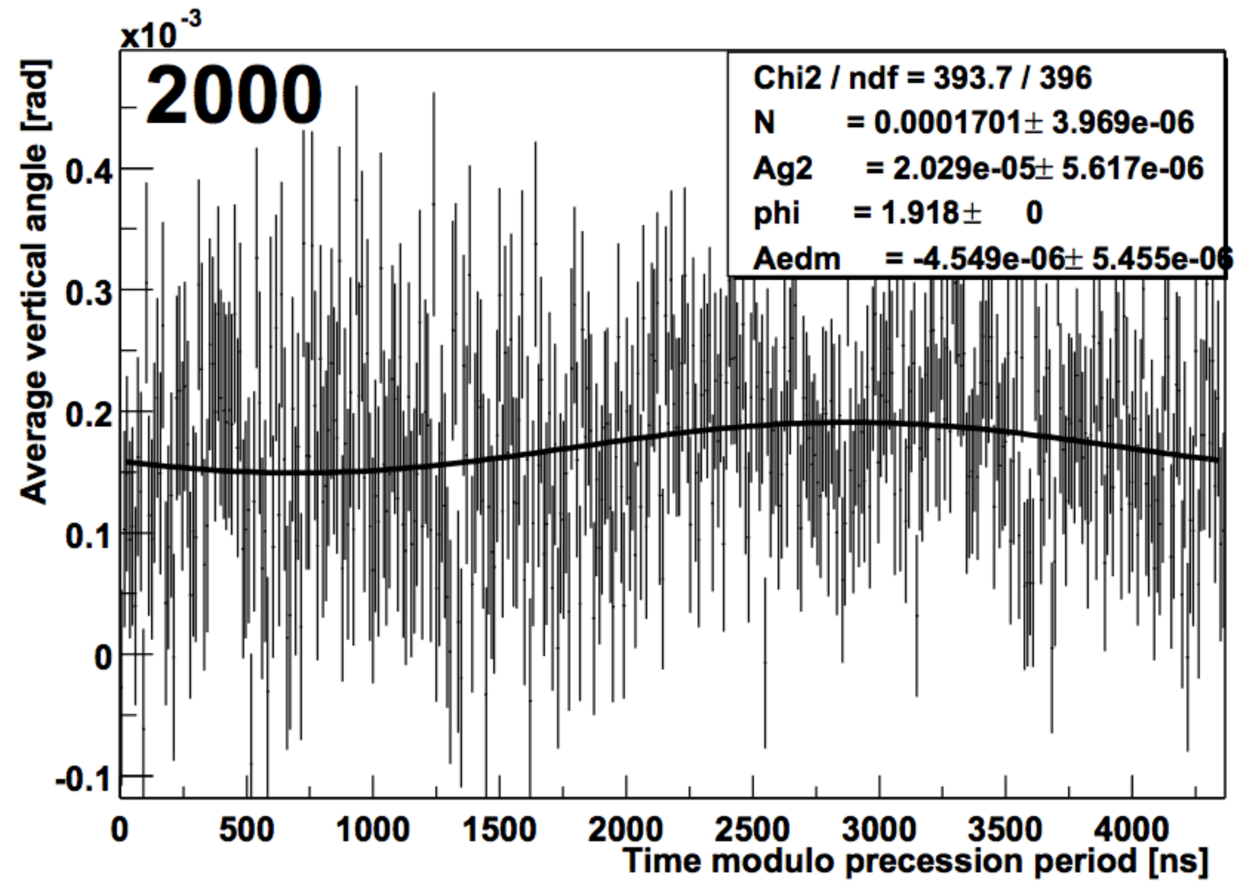
PLB 831 (2022) 137194

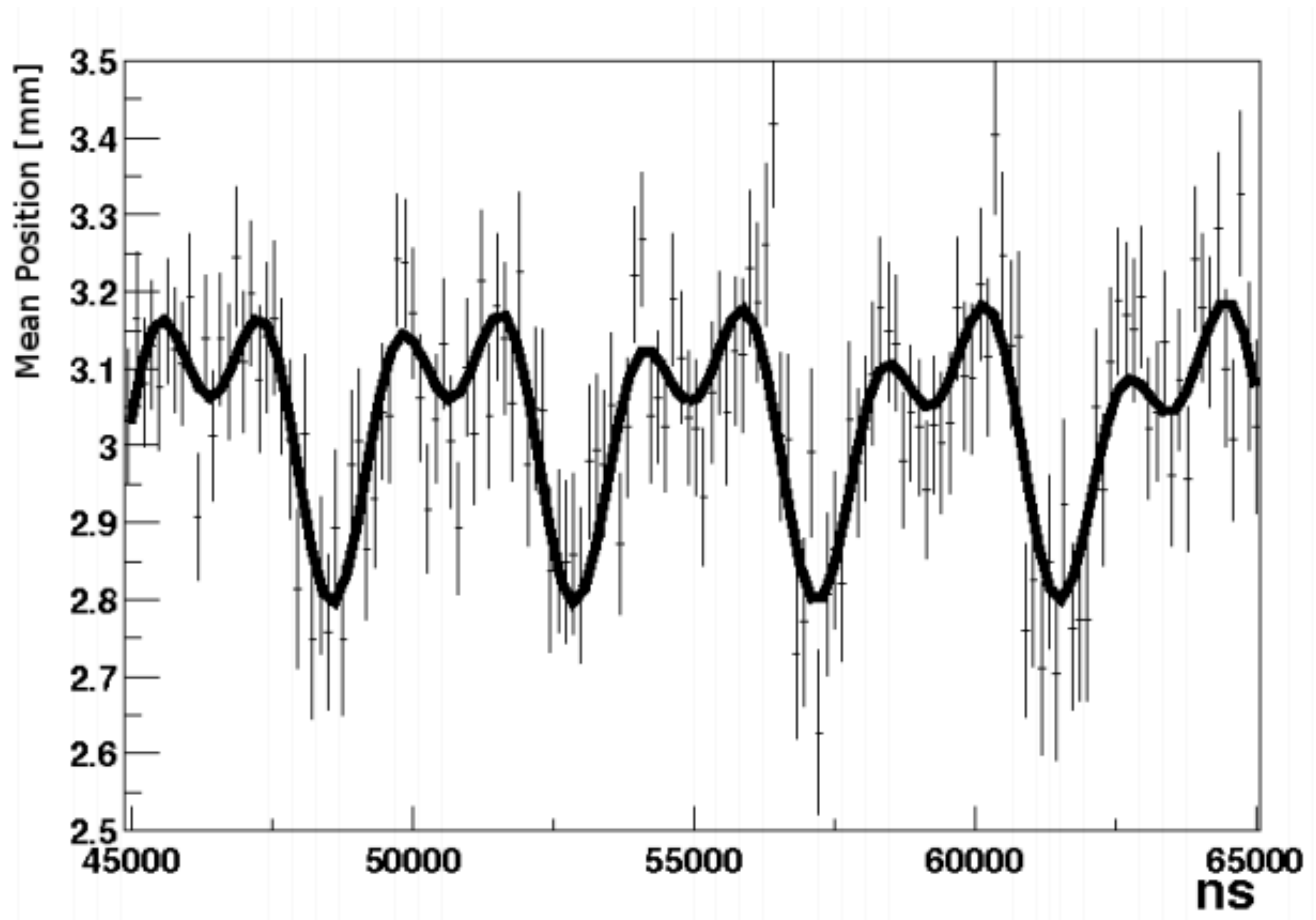
BNL/Fermilab Muon EDM search

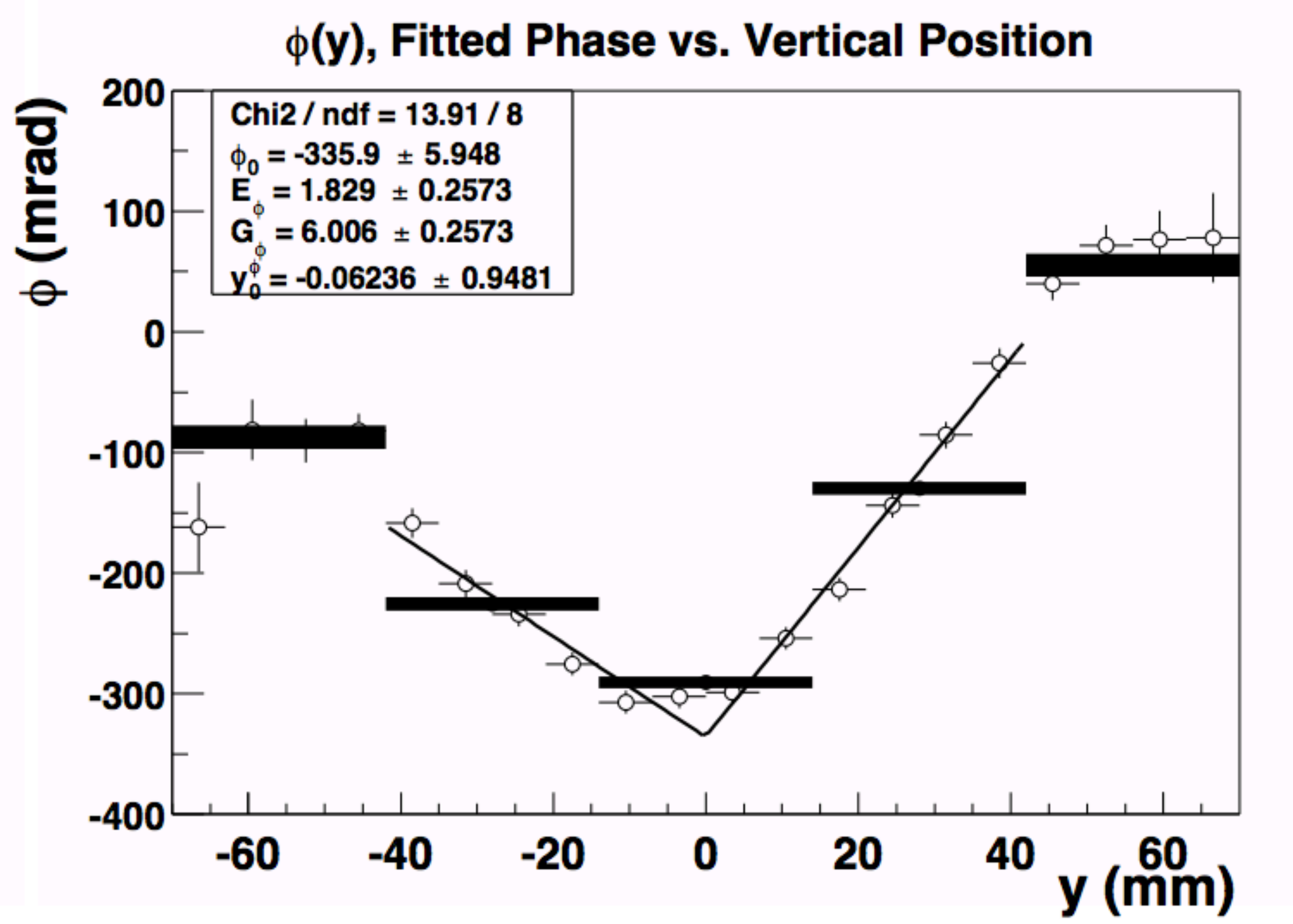
PRD 80 (2009) 052008



- Three approaches from BNL/FNAL experiment:
  - Vertical Angle Oscillation (Tracker) **Talk from Sam Grant**
  - Vertical Position Oscillation (Calorimeter)
  - Vertical Phase Gradient (Calorimeter)







$$\theta(t) = M + A_\mu \cos(\omega t + \Phi) + \boxed{A_{\mathrm{EDM}} \sin(\omega t + \Phi)}$$

$$f(t) = K + [\boxed{S_{g2}\sin(\omega t)} + C_{g2}\cos(\omega t)] + e^{-(t/\tau_{\mathrm{CBO}})} \times [S_{\mathrm{CBO}}\sin(\omega_{\mathrm{CBO}}(t-t_0)+\Phi_{\mathrm{CBO}}) + C_{\mathrm{CBO}}\cos(\omega_{\mathrm{CBO}}(t-t_0)+\Phi_{\mathrm{CBO}})] + Me^{-(t/\tau_M)}$$

$$\phi(y) = \phi_0 + \boxed{E_\phi(y-y_0^\phi)} + |G_\phi(y-y_0^\phi)|$$

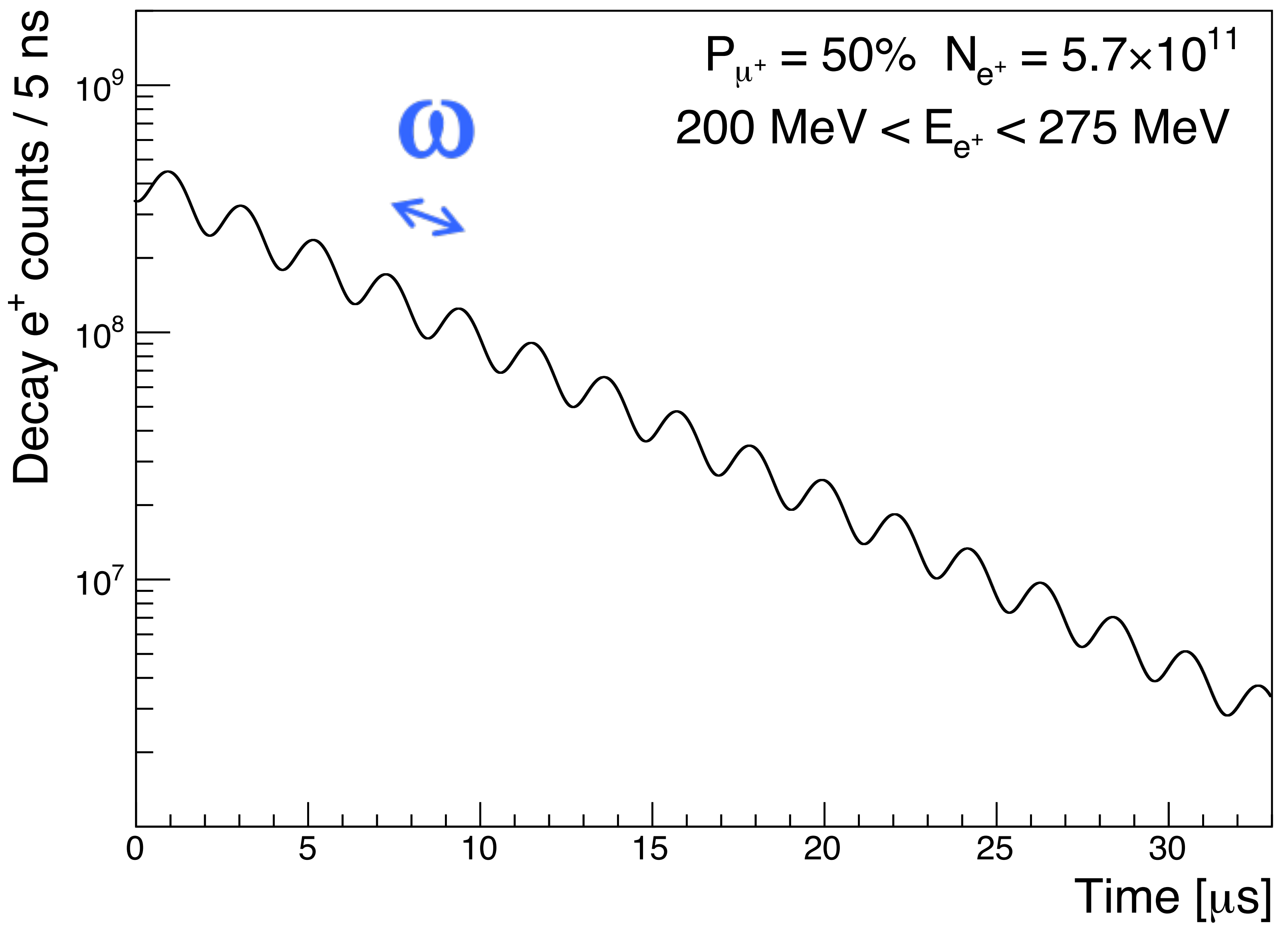
J-PARC Muon EDM search

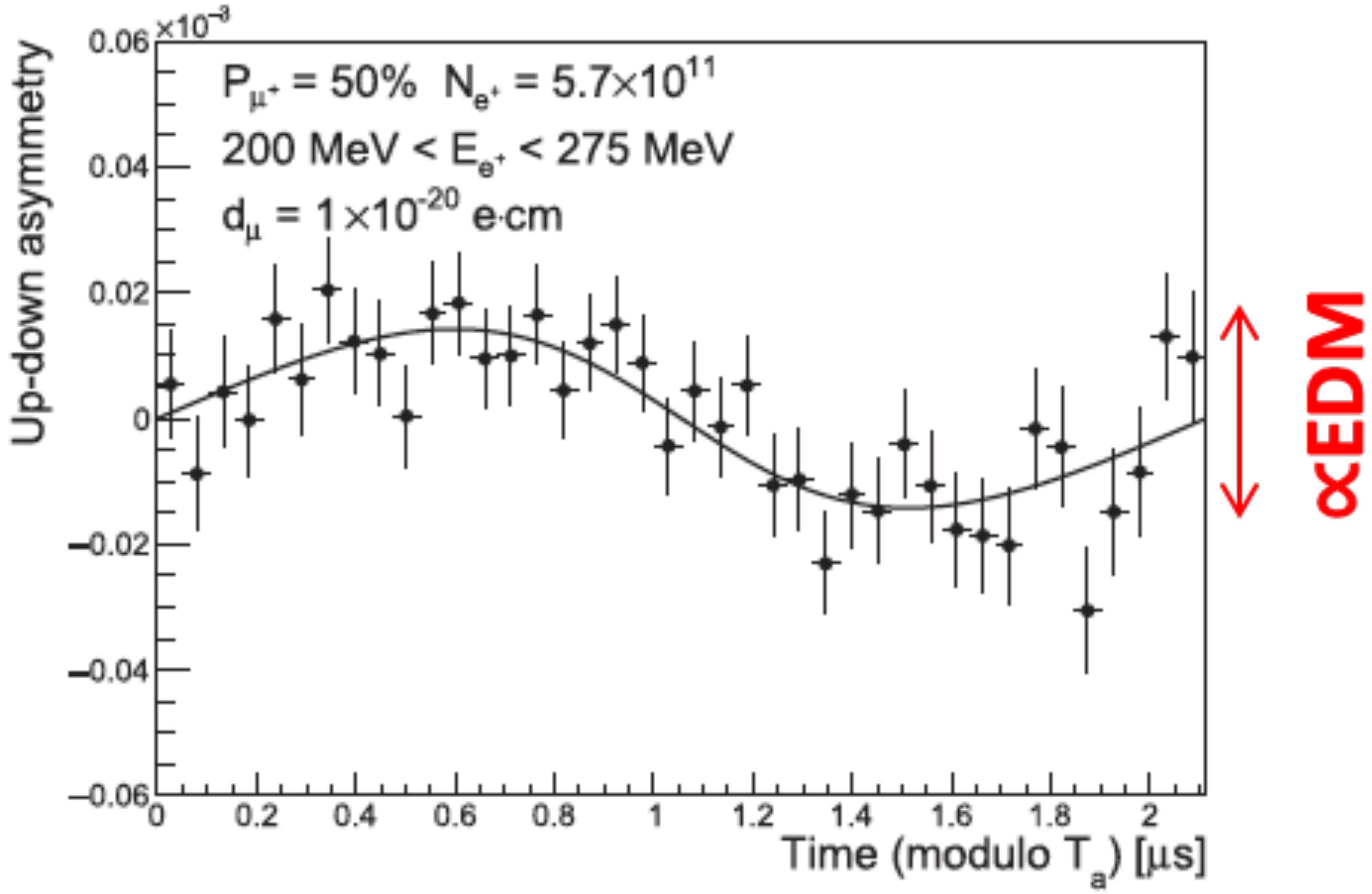
PTEP 2019 (2019) 5, 053C02

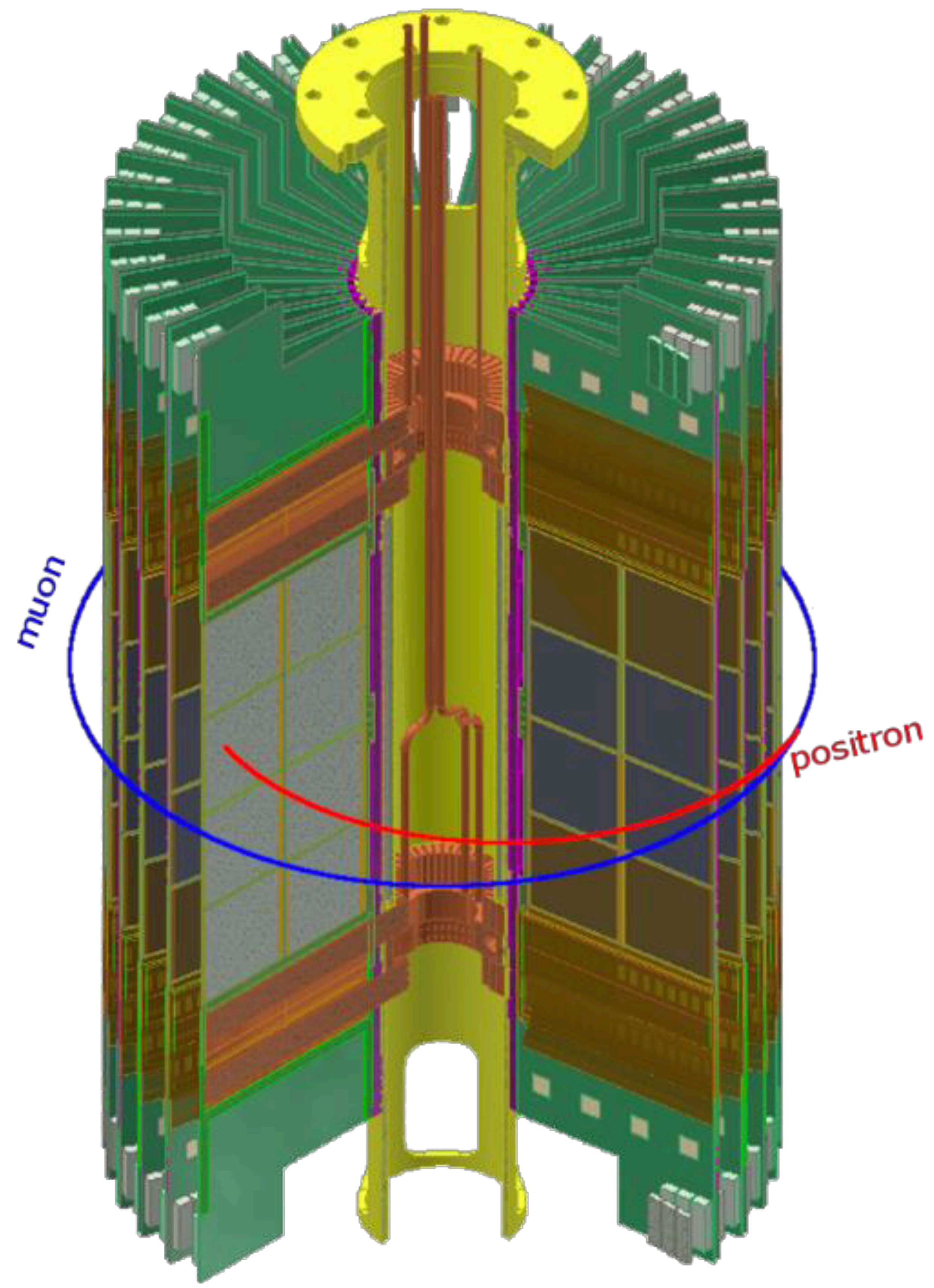
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

p = 300 MeV/c muon
No electrostatic quadrupole

Talk from Ce Zhang







Tracker-only measurement

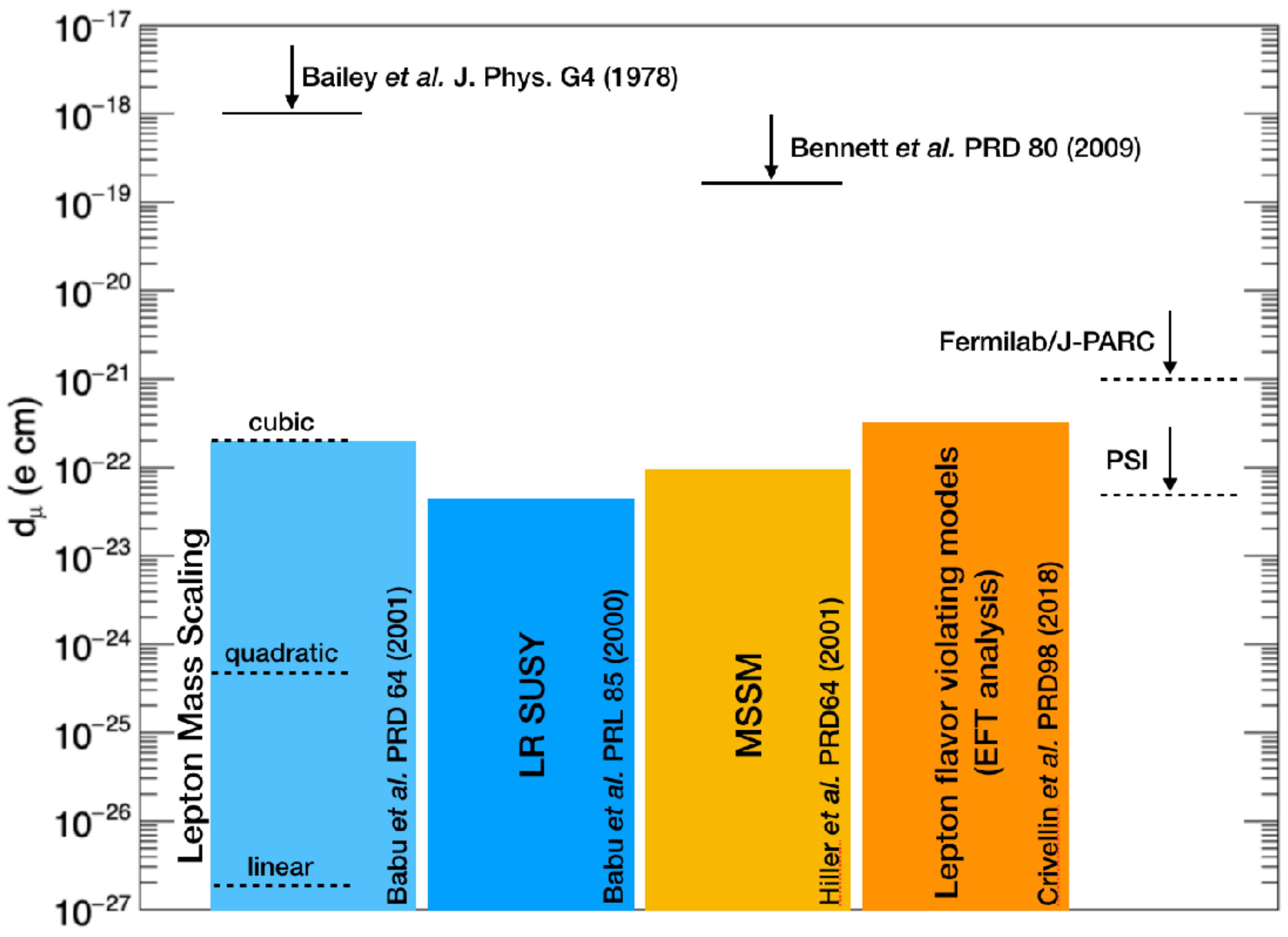
Uncertainties on a_μ [ppb]	450 (stat.)
	< 70 (syst.)
Uncertainties on EDM [10^{-21} e·cm]	1.5 (stat.)
	0.36 (syst.)

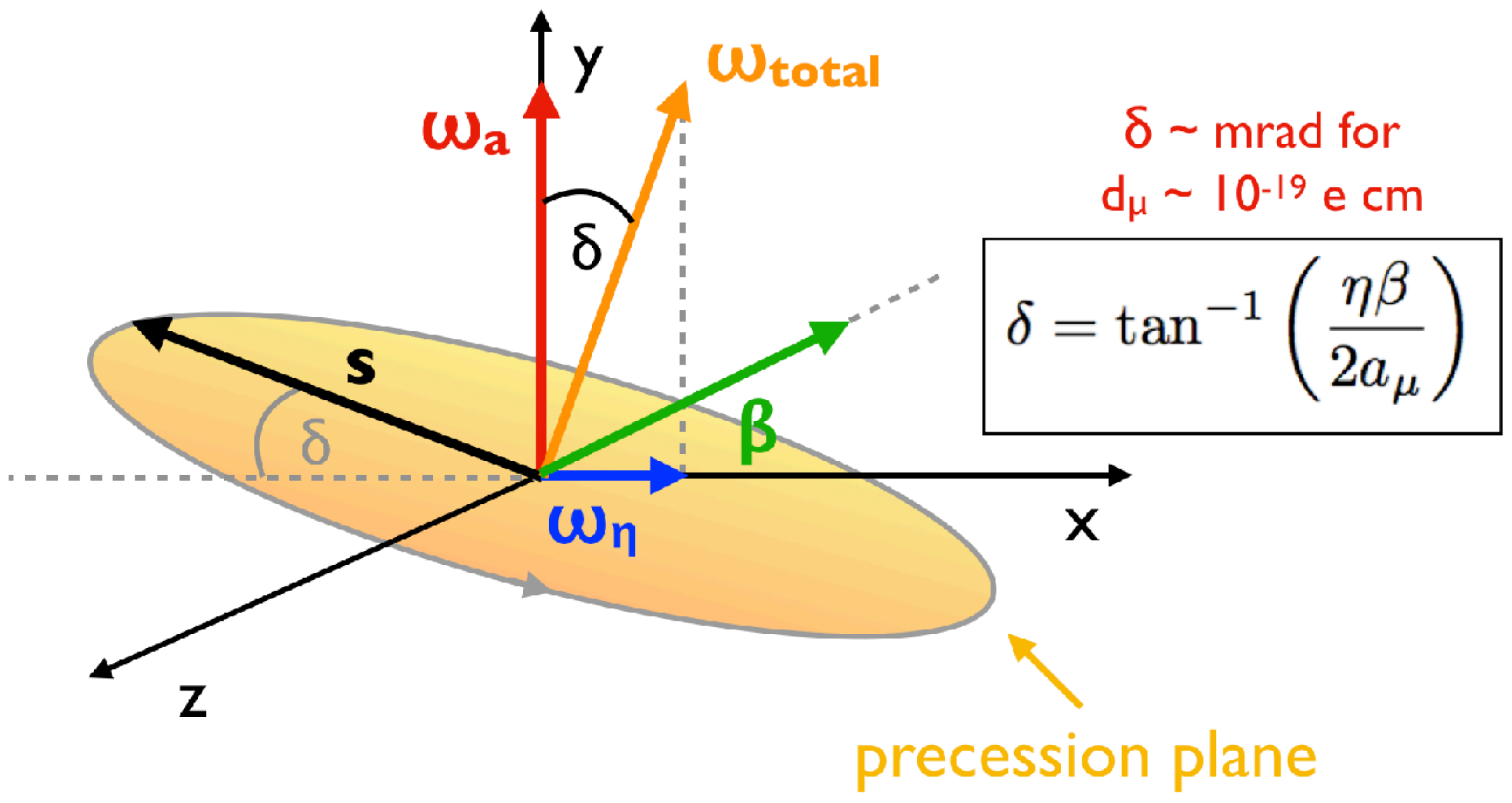
Detector misalignment

Systematics from axial E-field and radial B-field can be neglected

Can we going beyond 10^{-21} e cm?

- How can we improve the sensitivity of the muon EDM search?
- In the parasitic approach, the tilt angle is the limiting factor
- For an EDM below 10^{-21} e cm, it will be very challenging to measure this small angle (multiple scattering effect + systematics like alignment)





The “frozen-spin” technique

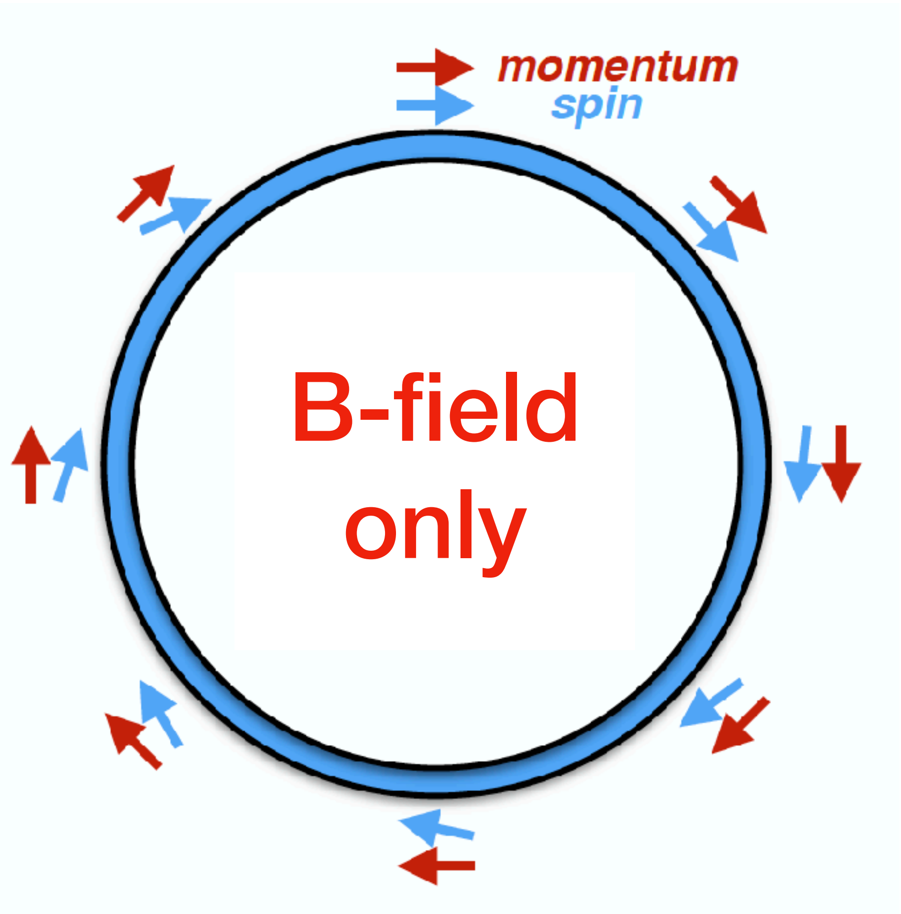
PRL 93 (2004) 052001

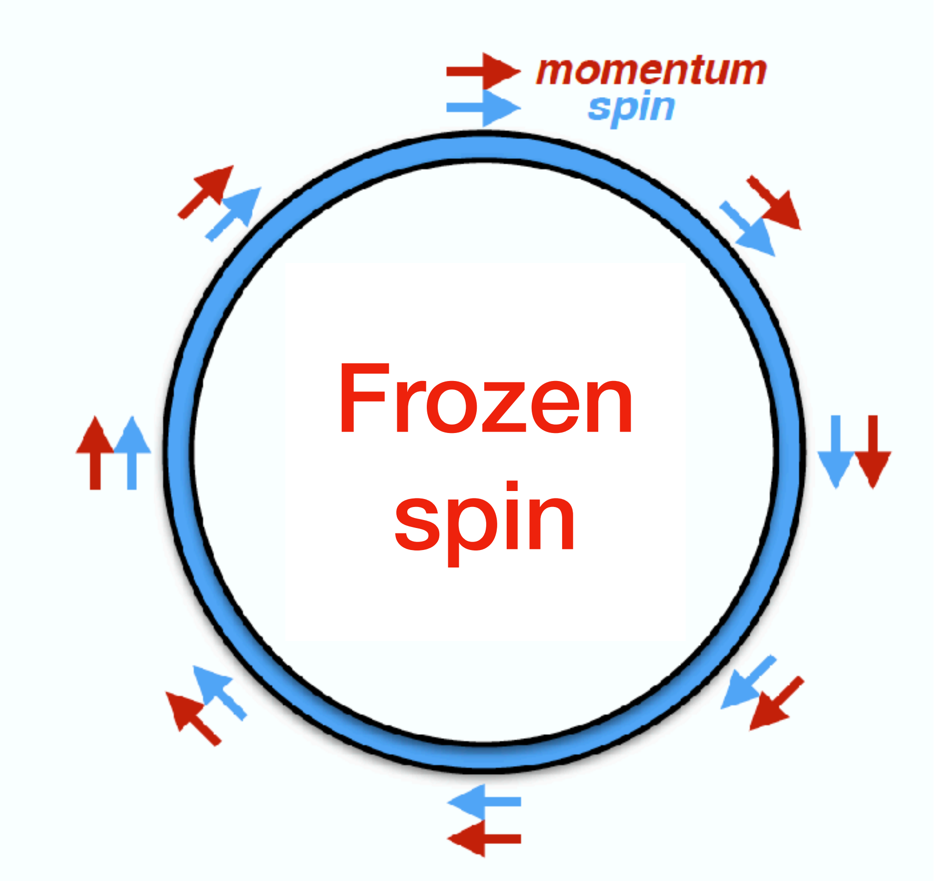
$$\vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m}\left\{ \cancel{\boxed{a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}} + \boxed{\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)} \right\}$$

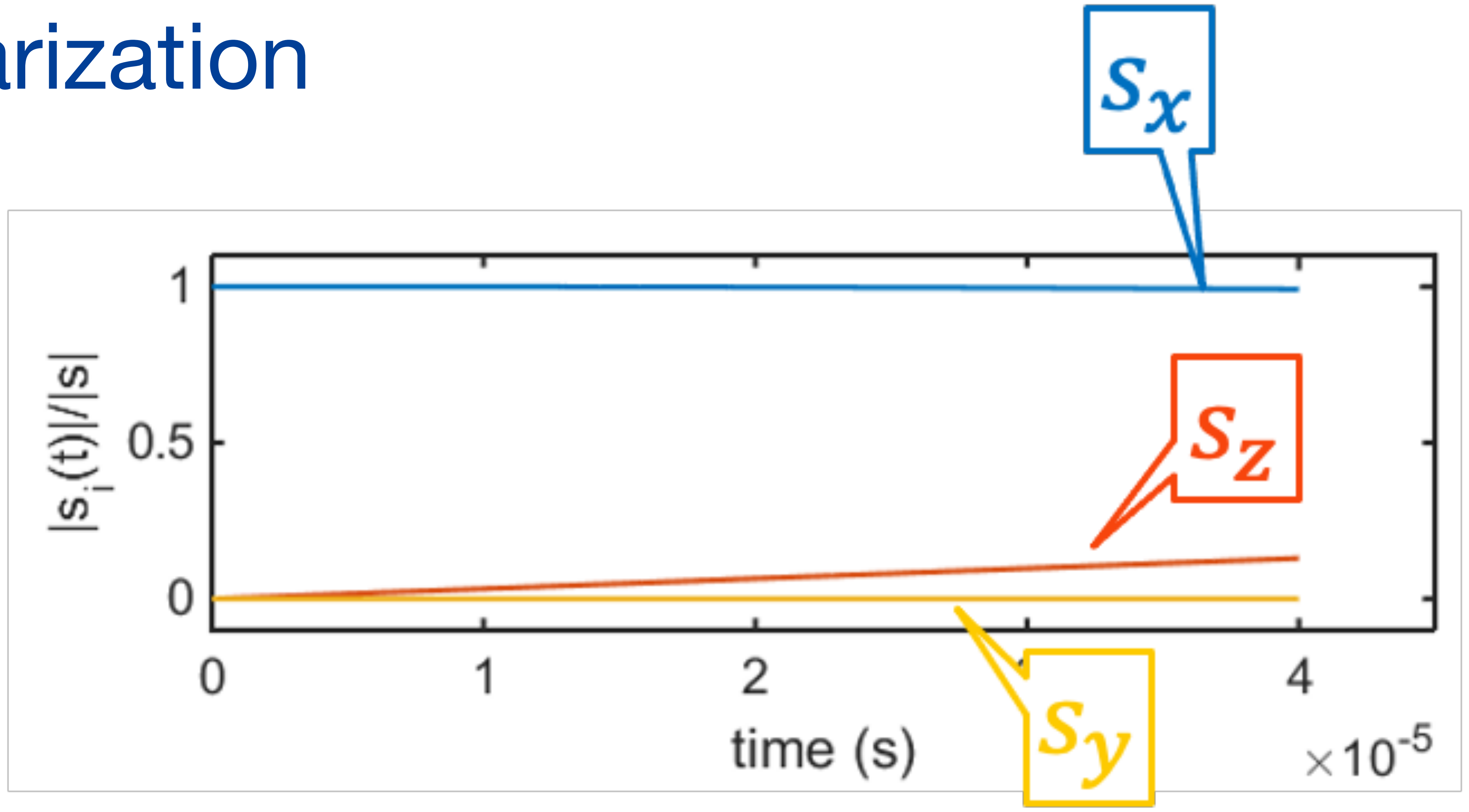
ω_a : g-2

ω_η: EDM

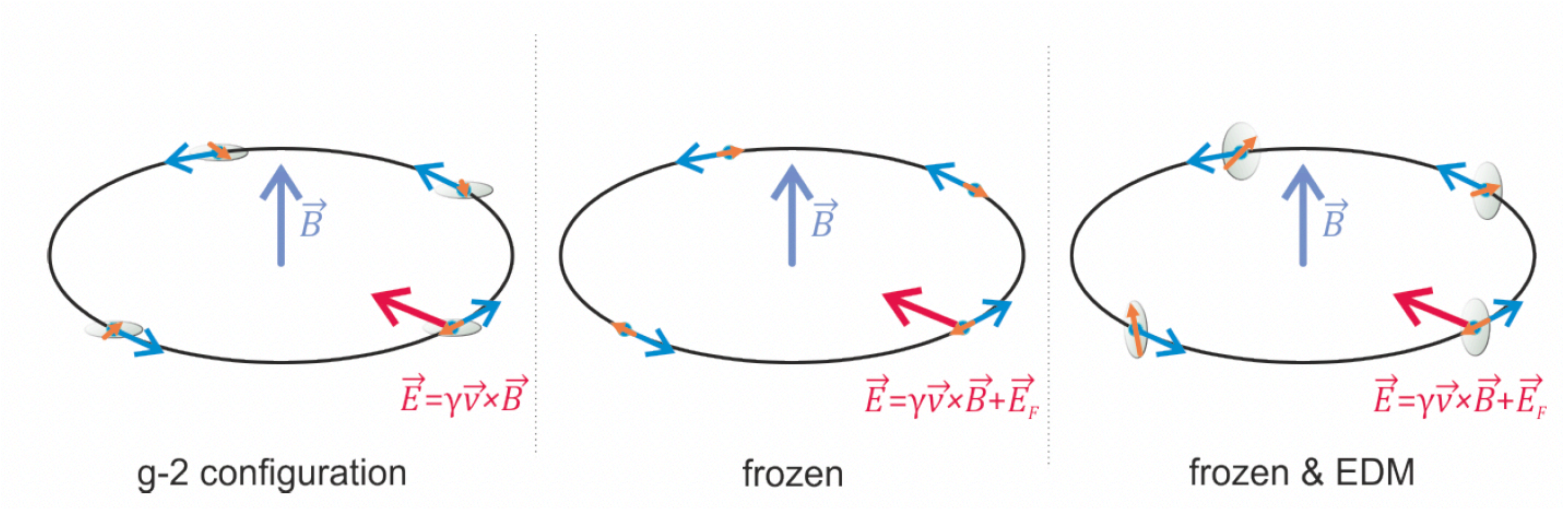
- Developed in 2004 for the muon
- Freeze g-2 component by applying a radial E-field of ~ **$aBc\beta\gamma^2$**
  → no anomalous precession in the storage plane
  → EDM causes an increasing vertical polarization







Putting everything together



Principle of the FS-EDM measurement

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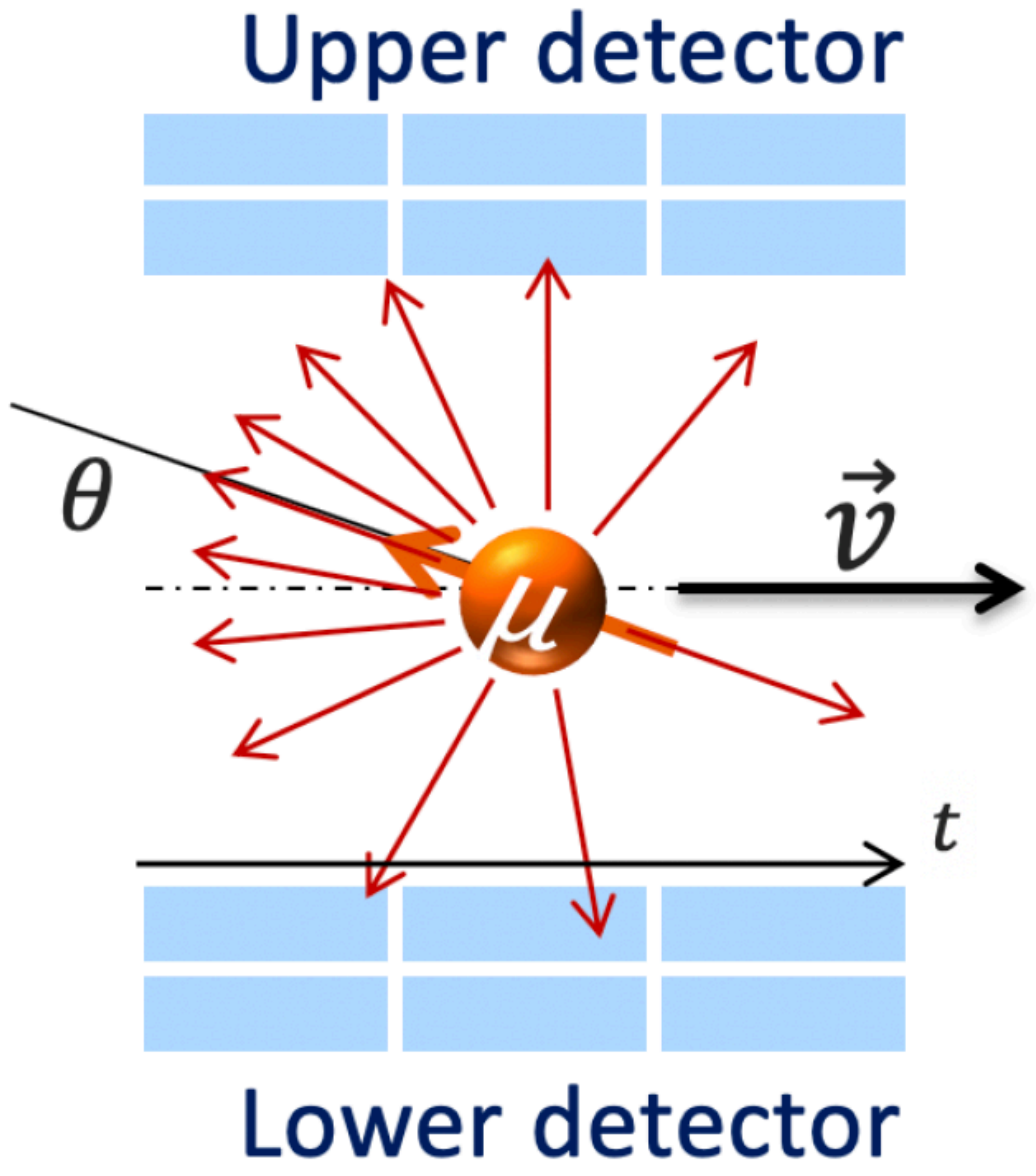
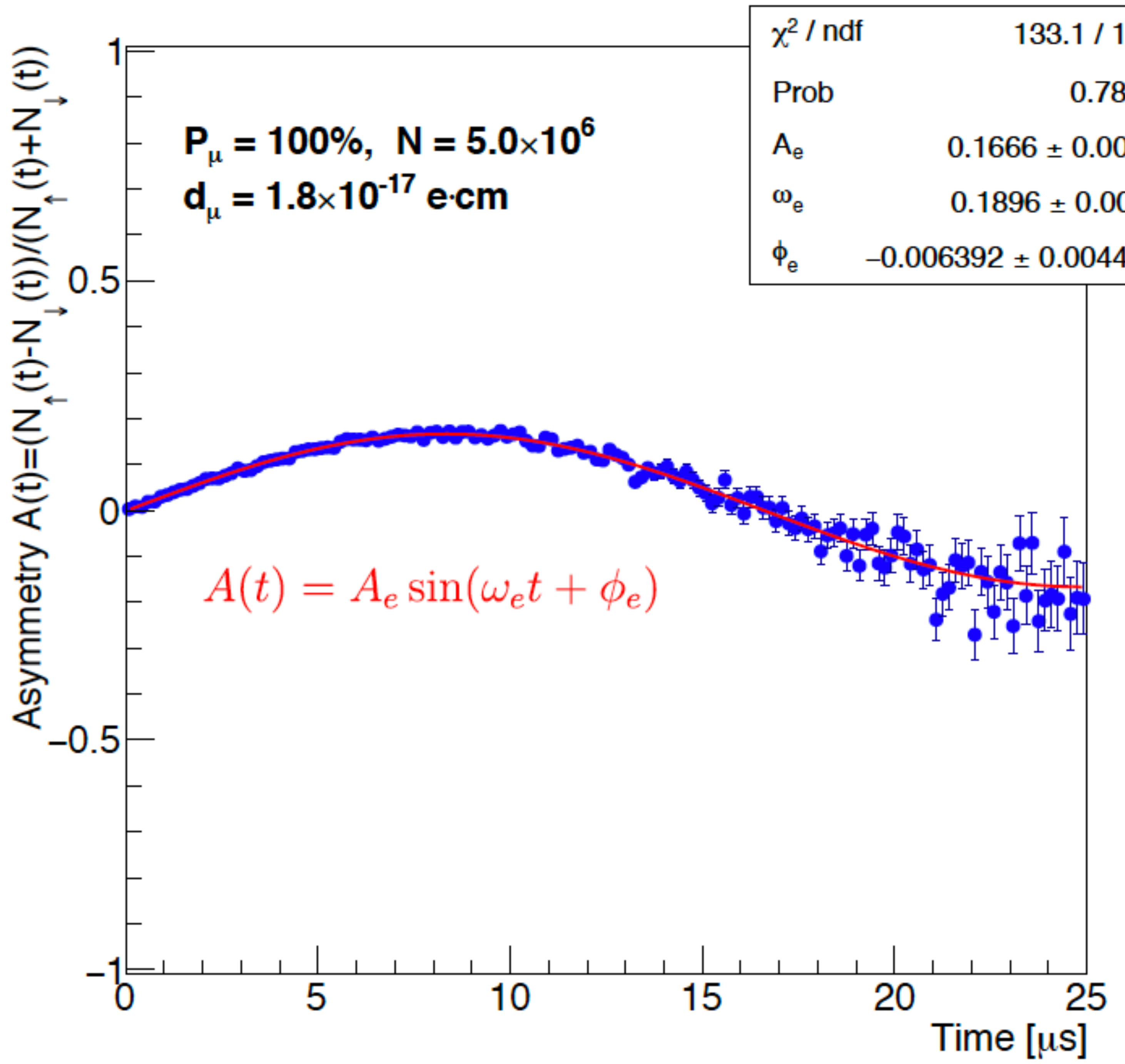
- Up-down asymmetry measured using upper and lower detectors





$$\sigma(d_\mu) = \frac{\hbar \gamma^2 a_\mu}{2 P E_f \sqrt{N}\, \gamma \tau_\mu\, \alpha}$$

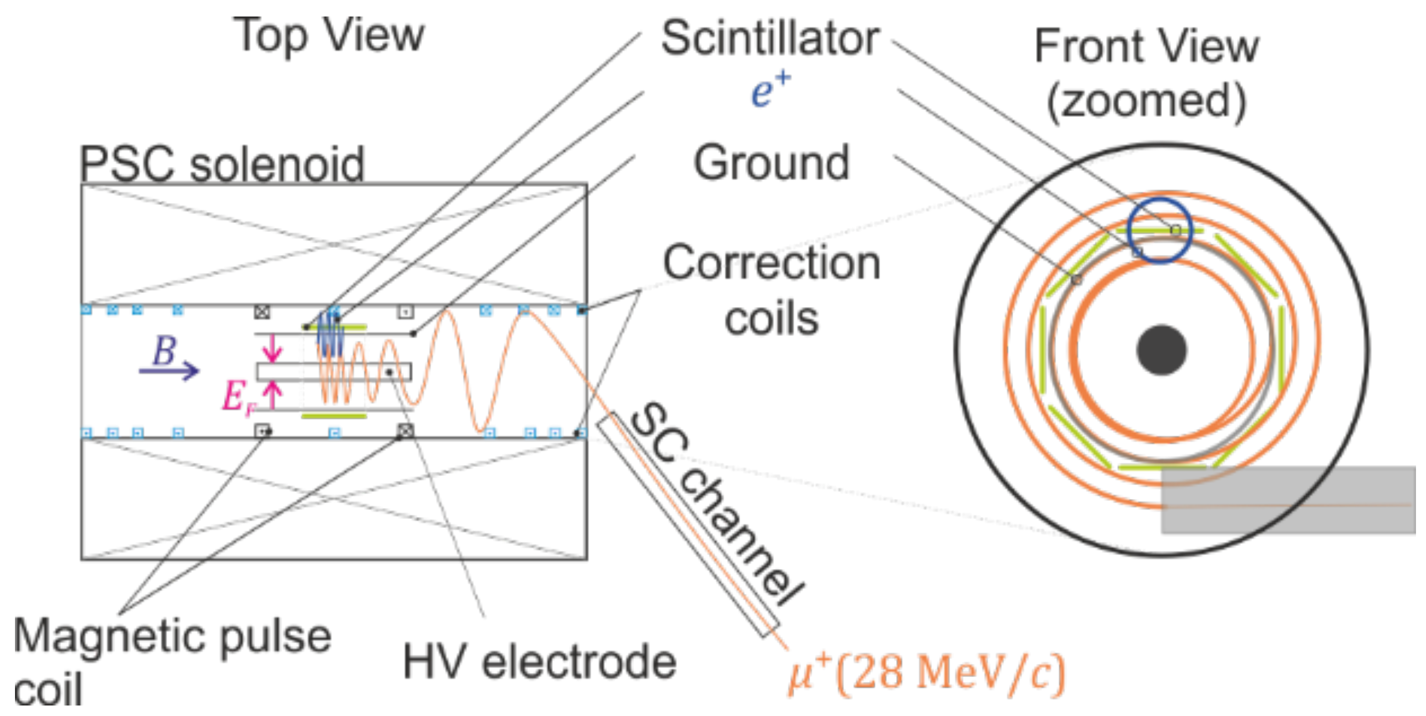
P := initial polarization
E_f := Electric field in lab
$\sqrt{N}$:= number of positrons
τ_μ := lifetime of muon
α := mean decay asymmetry

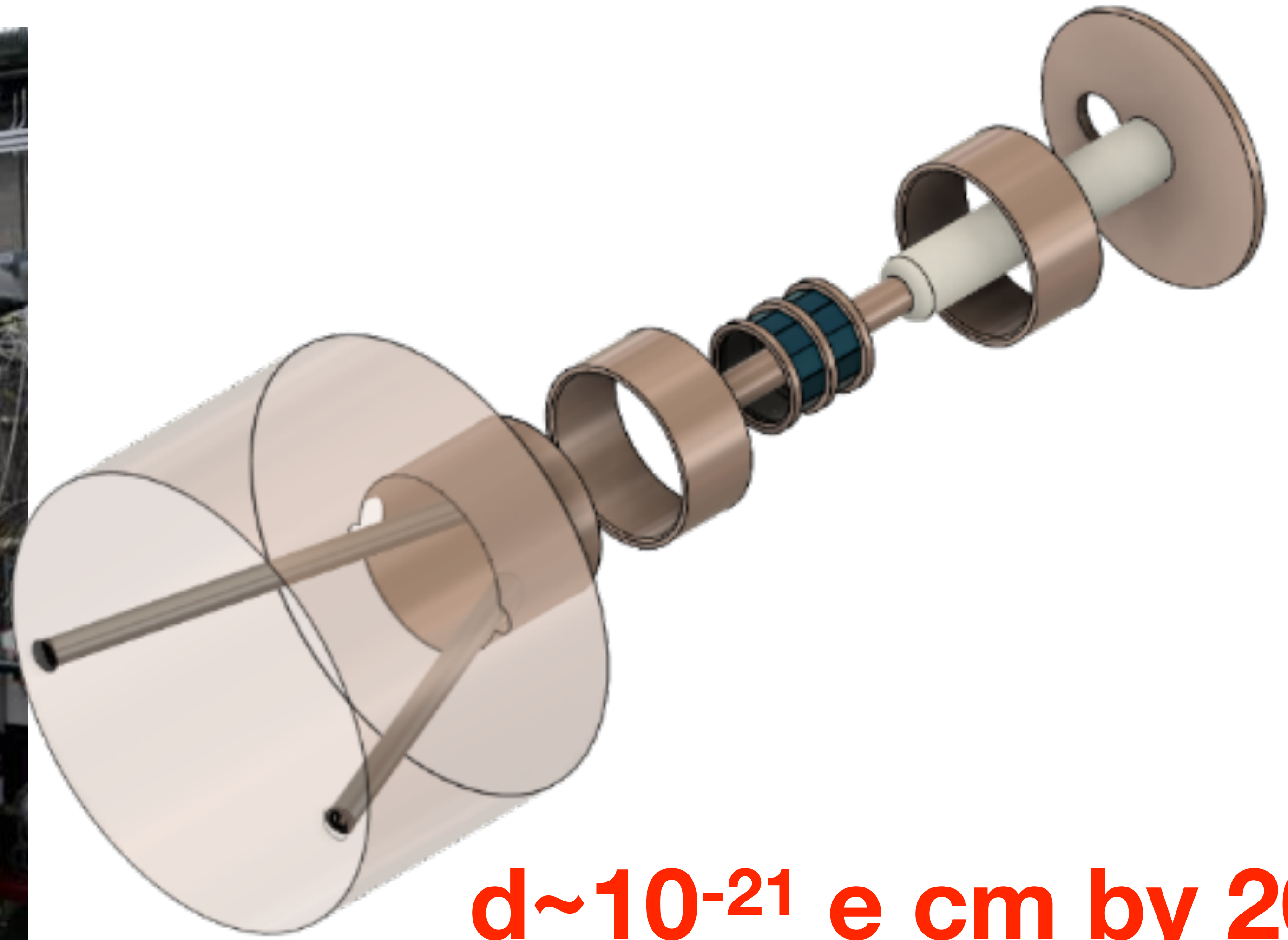
muEDM at PSI with the FS approach

Tsung-Dao Lee Institute

Muon EDM search at PSI will commence in two phases:

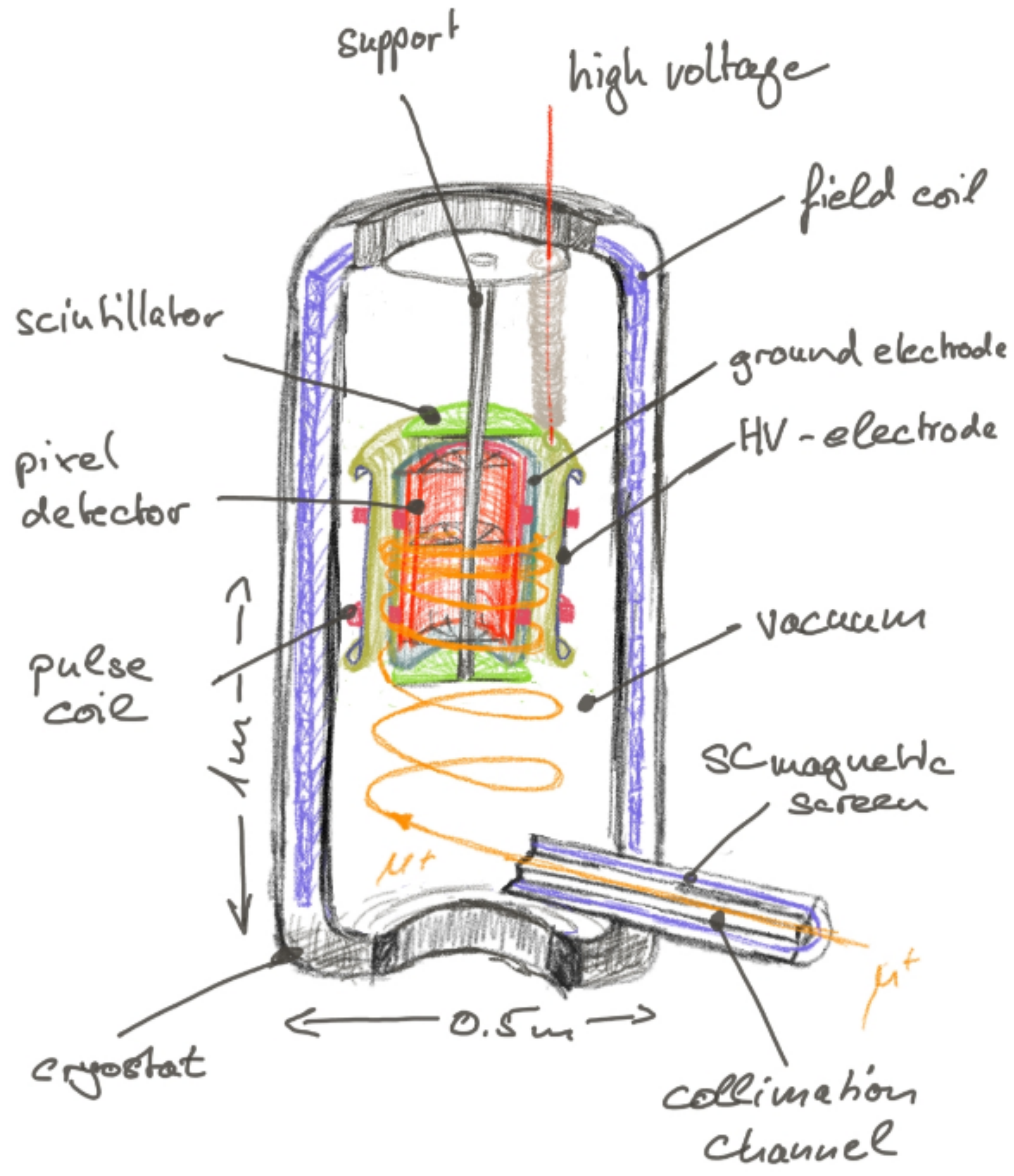
Phase 1 @ 28 MeV/c





d~10^{-21} e cm by 2026

Phase 2 @ 125 MeV/c



d~10^{-23} e cm by 2031

Potential beamlines for muEDM

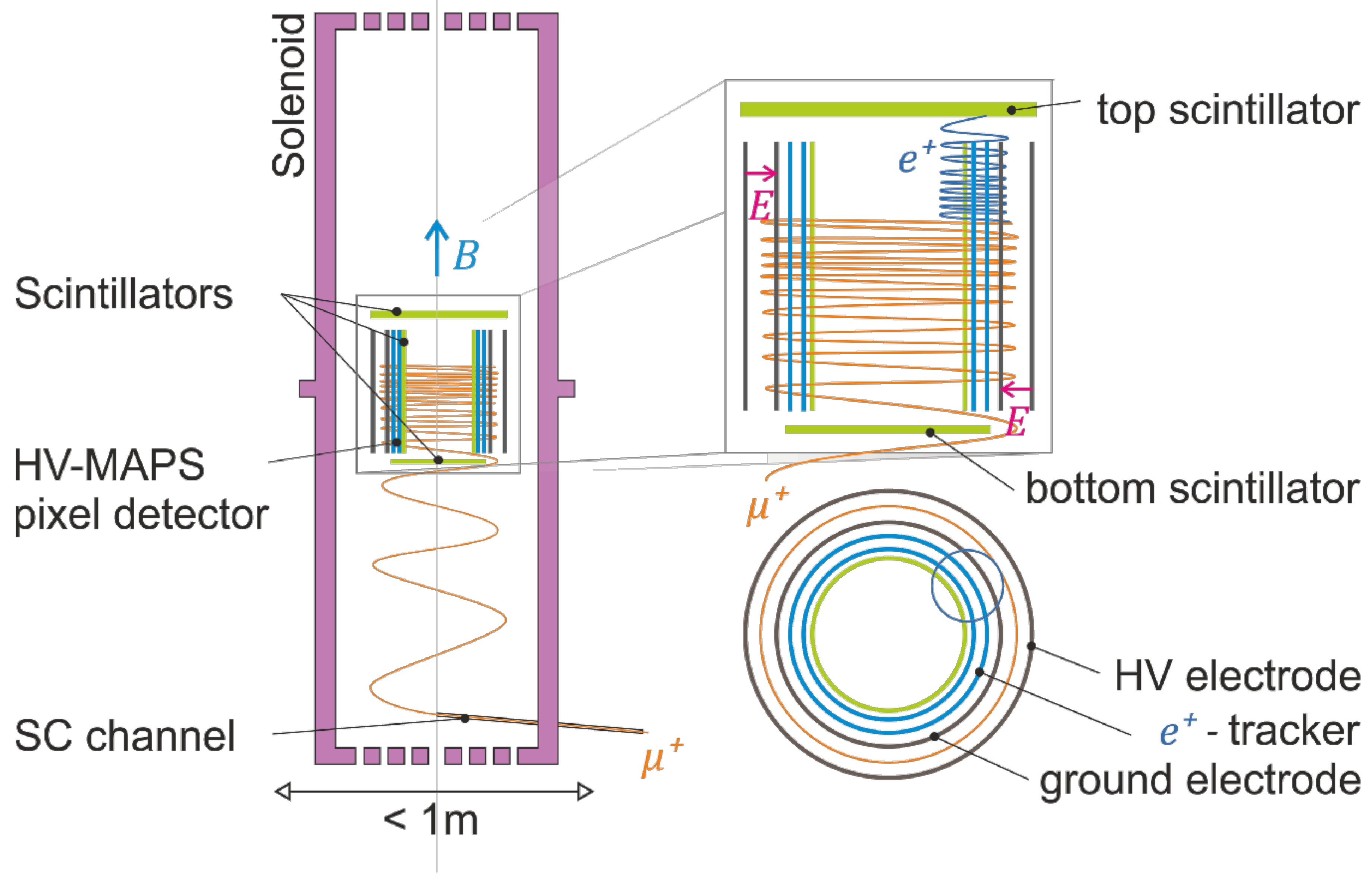
Phase 1 @ πE1
28 MeV/c, ~10^6/s

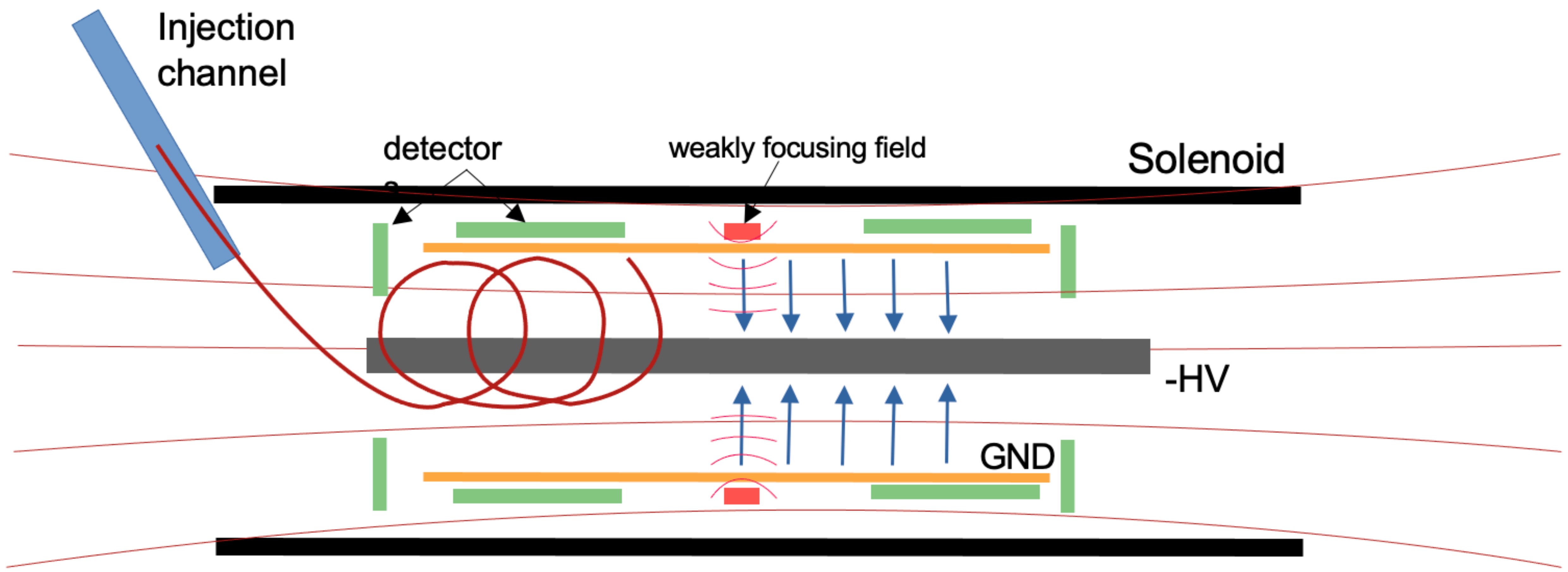
Phase 2 @ μE1
125 MeV/c, ~10^8/s

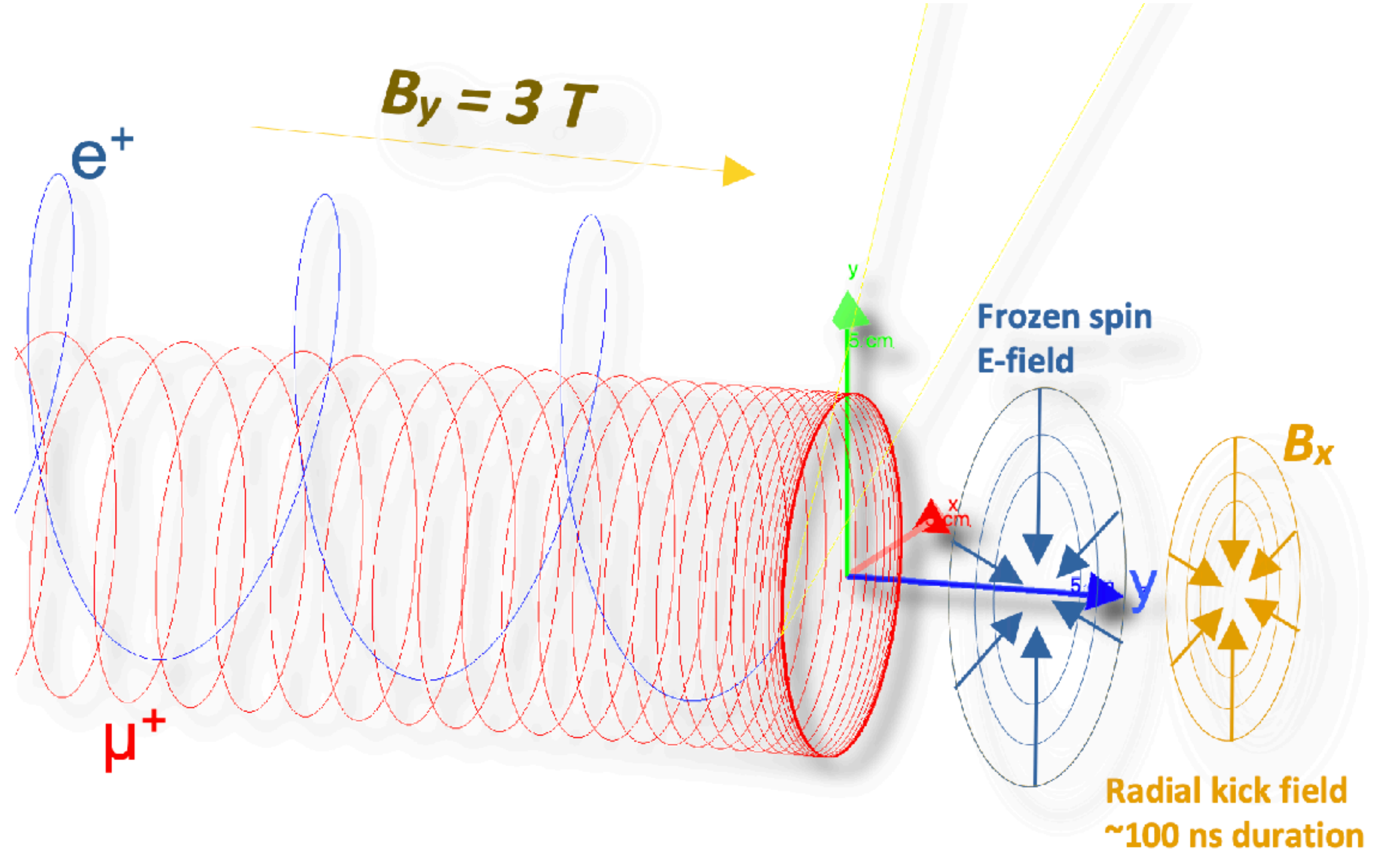
PSI Experimental Hall

The general experimental idea

- Muons enter the uniform magnetic field
- A radial magnetic field pulse stops them within a weakly focusing field where they are stored
- Radial electric field 'freezes' the spin so that the precession due to the g-2 is cancelled

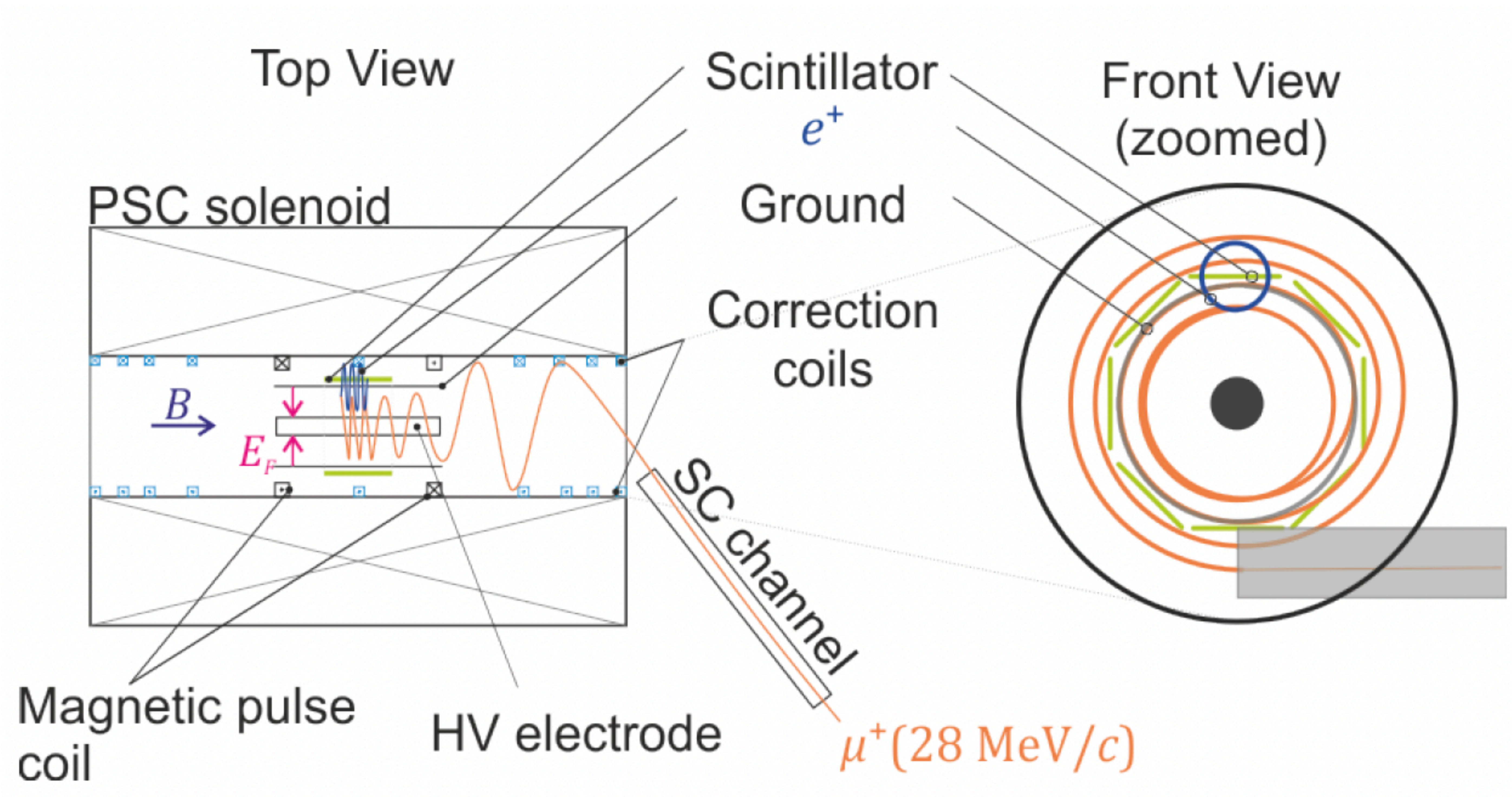






muEDM Precursor at PSI (Phase 1)

Proof-of-principle of the frozen spin technique

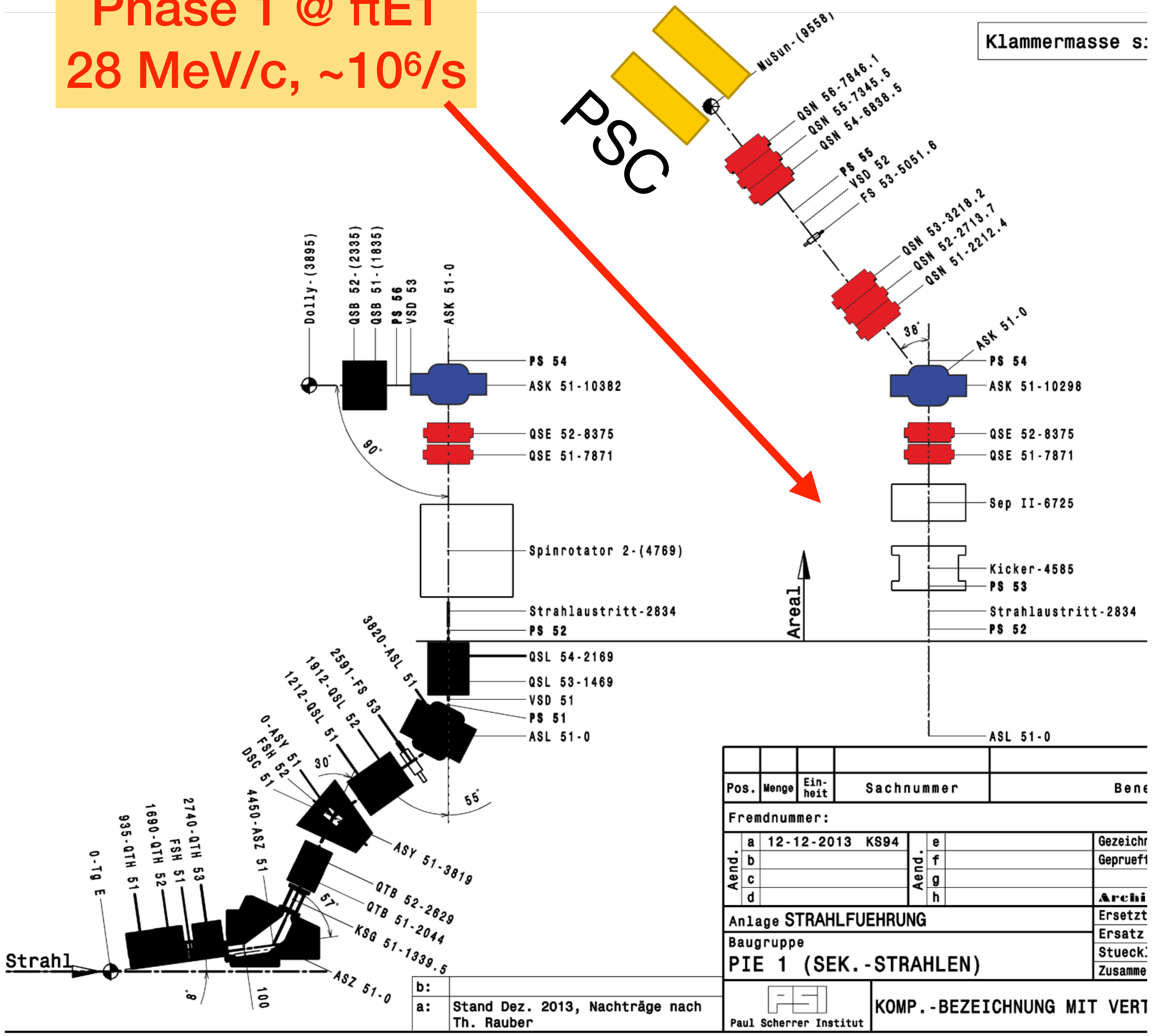


Develop key technologies and design the final instrument

- Full MC model
- Full FEM model
- Analysis and DAQ
- Nested electrode system with a minimal material budget for the frozen-spin technique
- Pulsed magnetic field to kick muons on a stable orbit
- Injection channel made of a superconducting shield

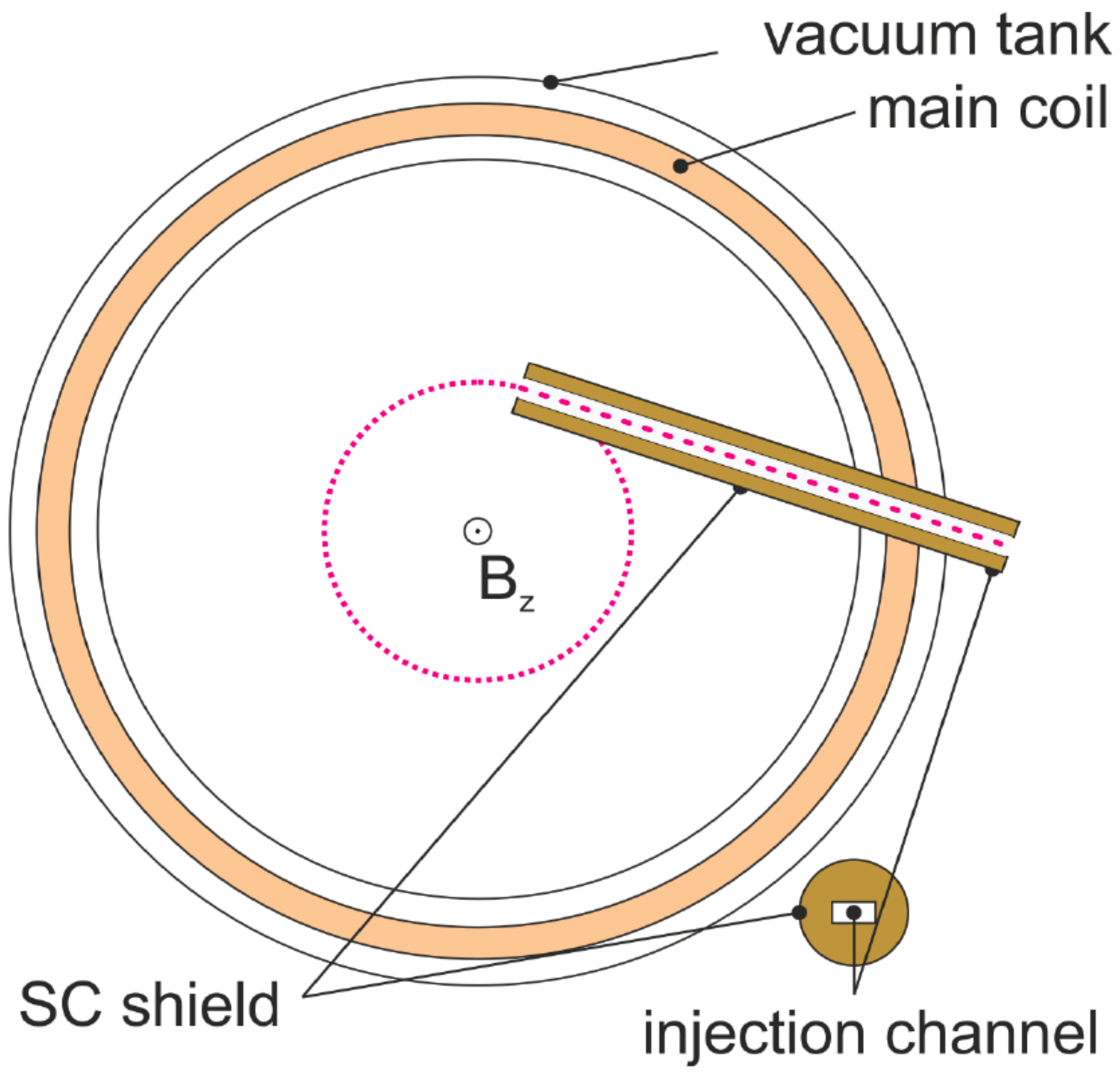
Precursor experiment at πE1@PSI

Phase 1 @ πE1
28 MeV/c, ~10^6/s

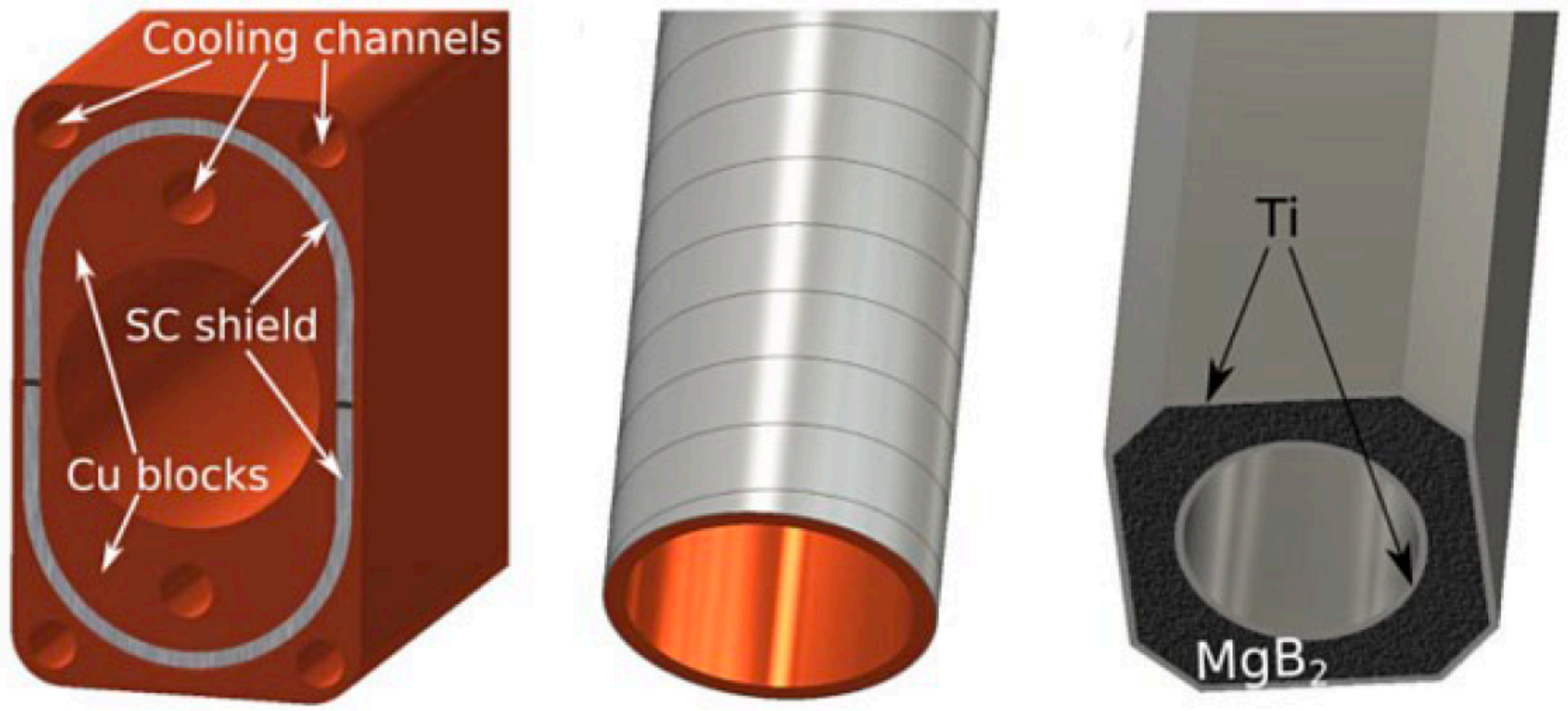


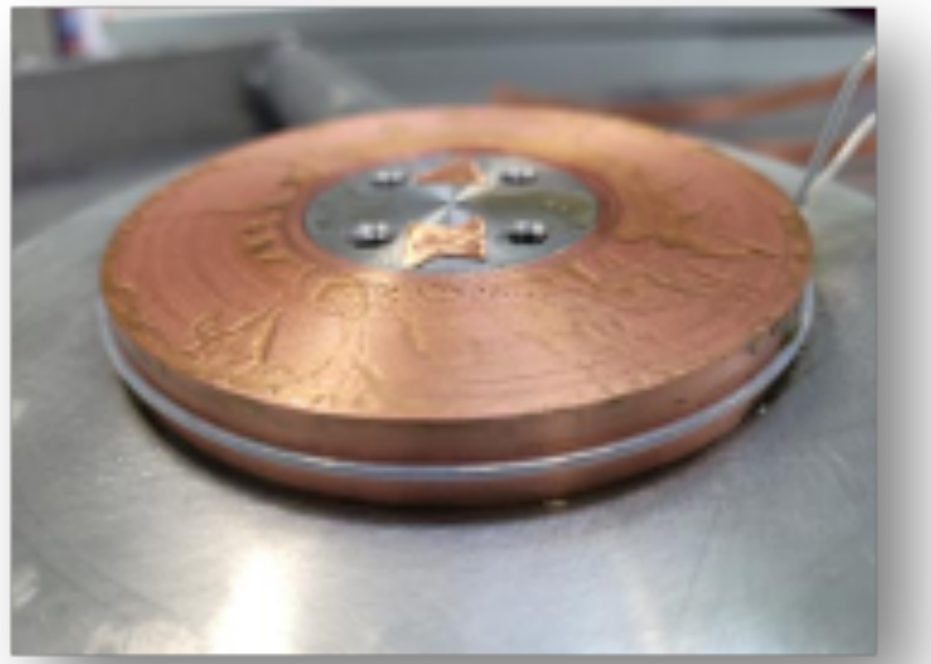
- Surface muon beam at $28\ \mathrm{MeV}/c$
- Muon rate $\sim 3 \times 10^6$
- Test bed for development
- Demonstration of storage and detection of g-2/EDM, e.g. with PSC magnet $\varnothing = 200\ \mathrm{mm}$
- The larger the bore the better for instrumentation!

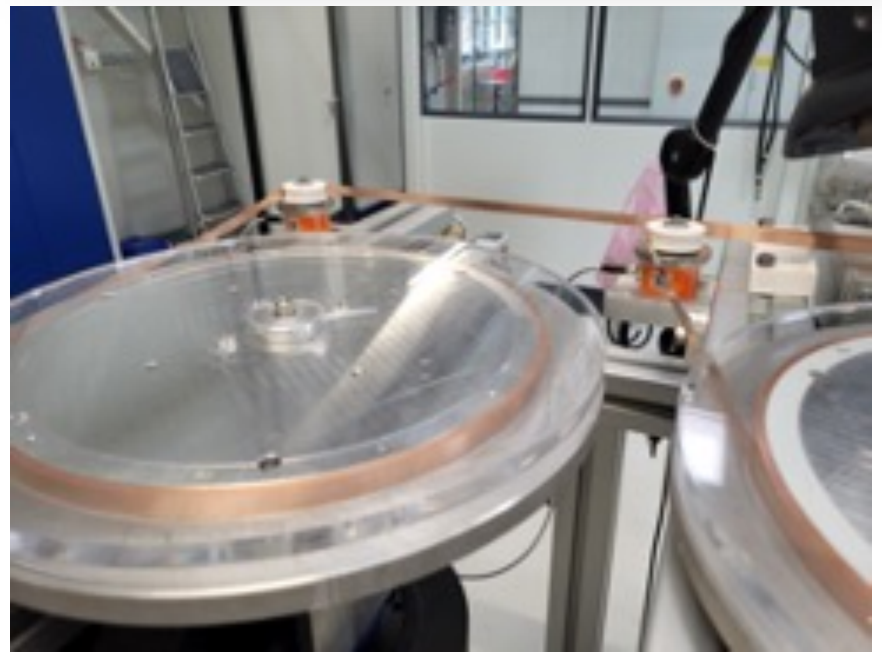
Muon beam injection



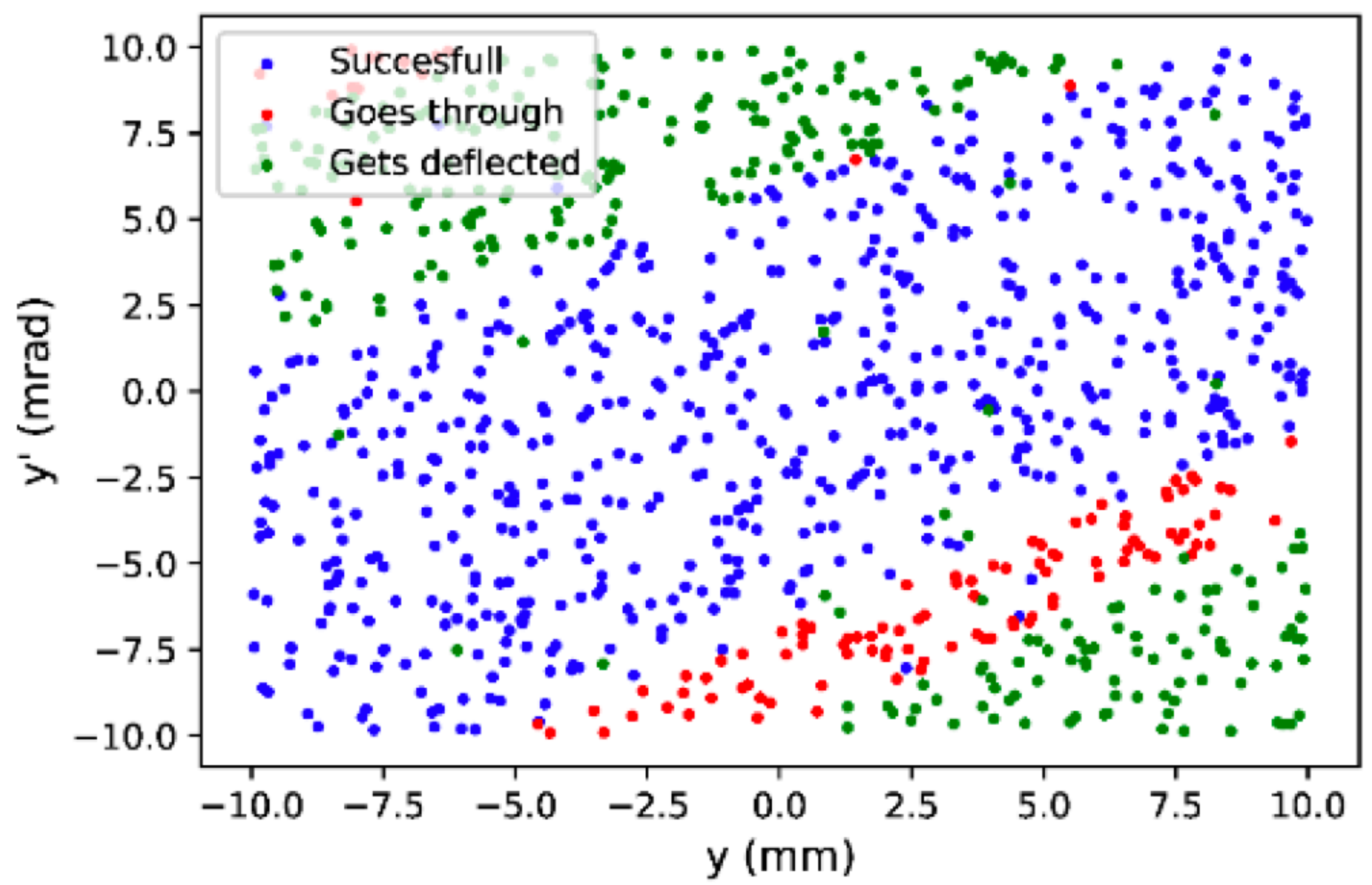
- Beam injection through “field-free” region
- Defines vertical and horizontal phase space for beam storage



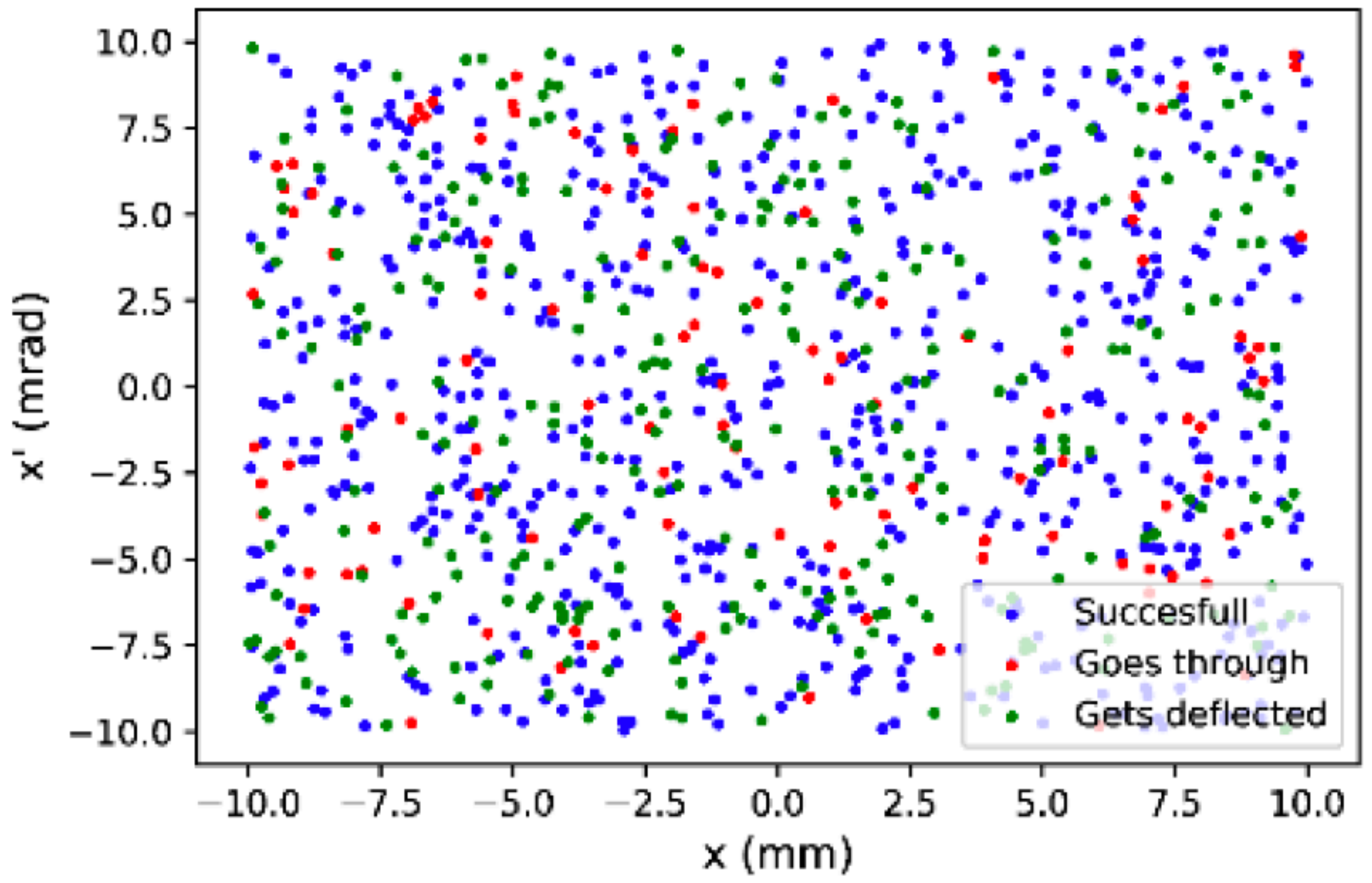




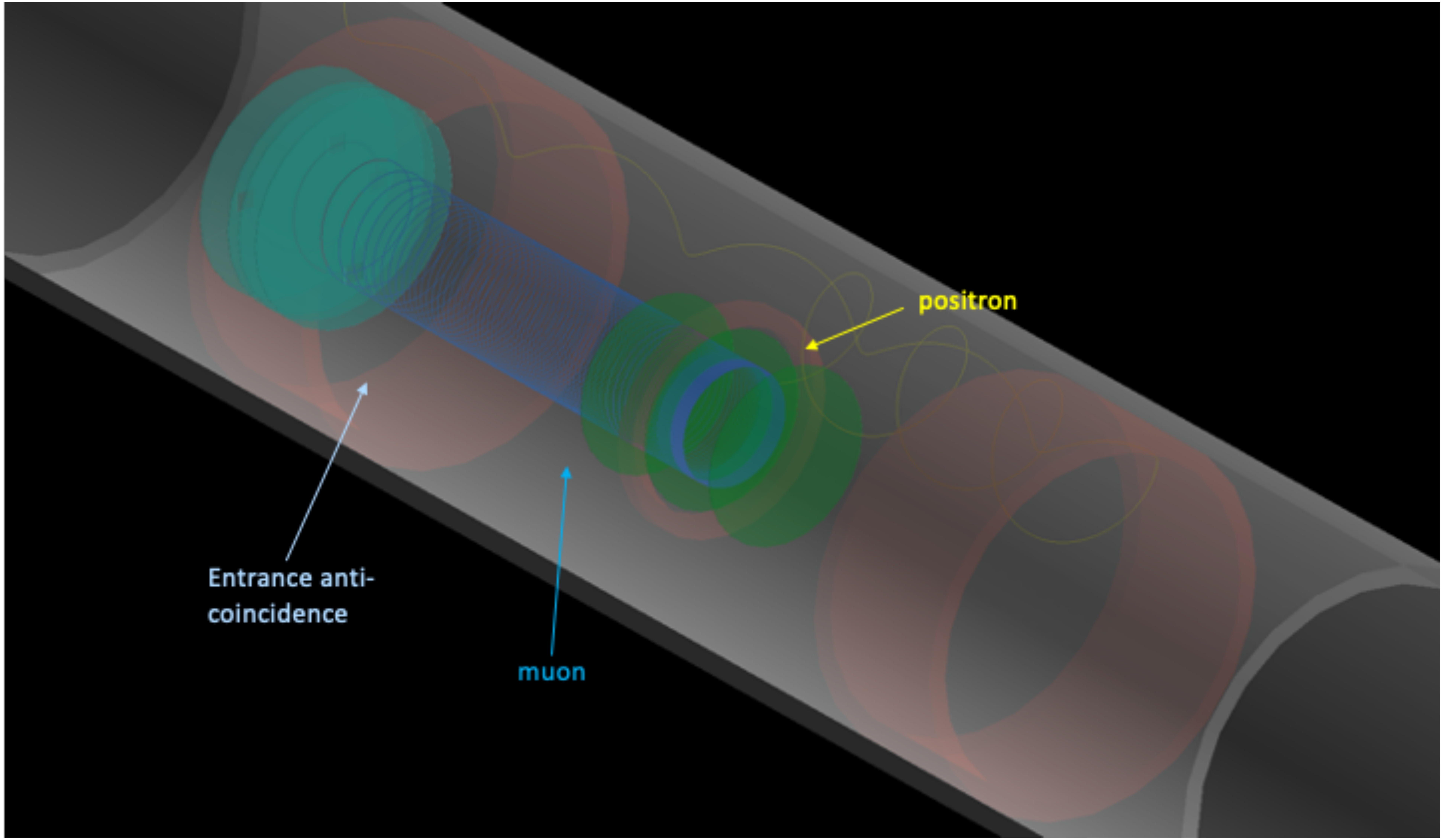
Vertical Phase Space



Horizontal Phase Space

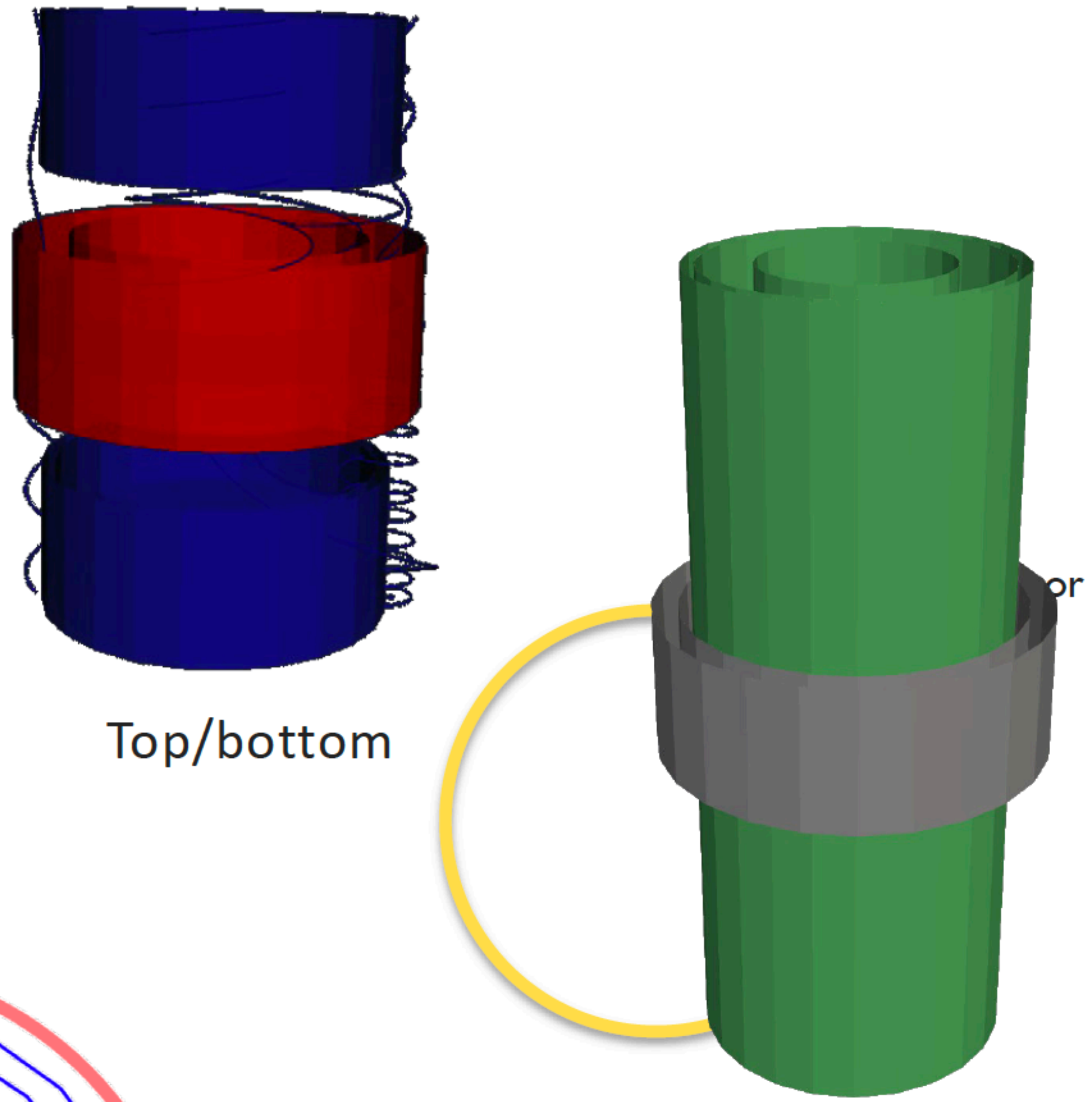


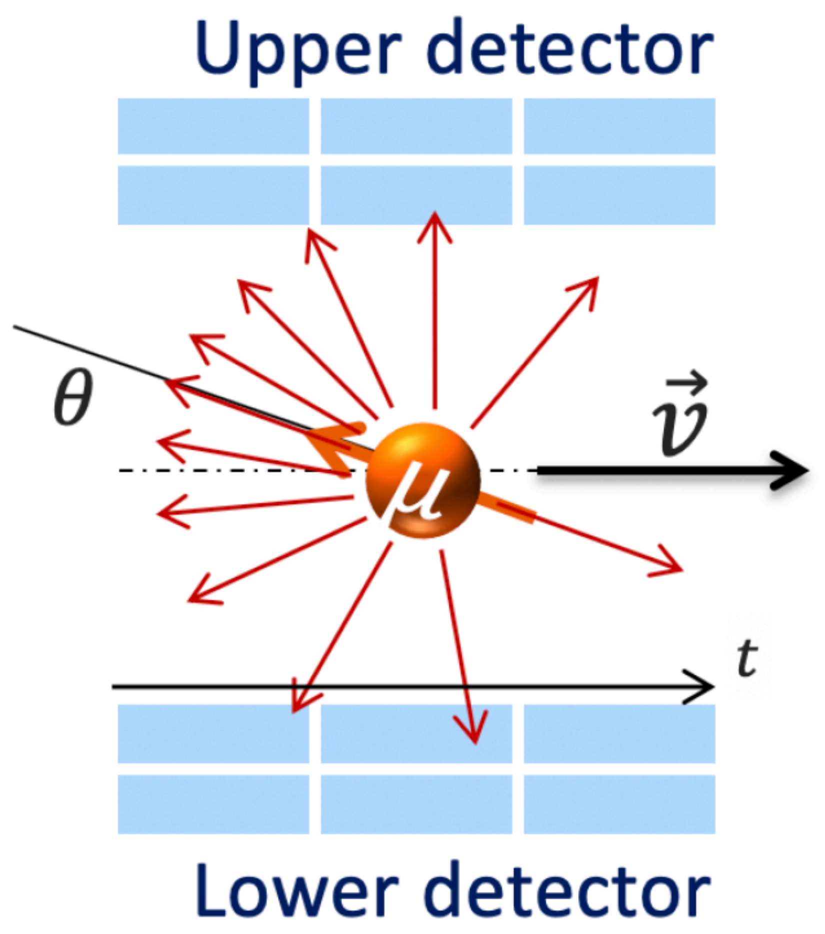
Entrance trigger and storage simulation

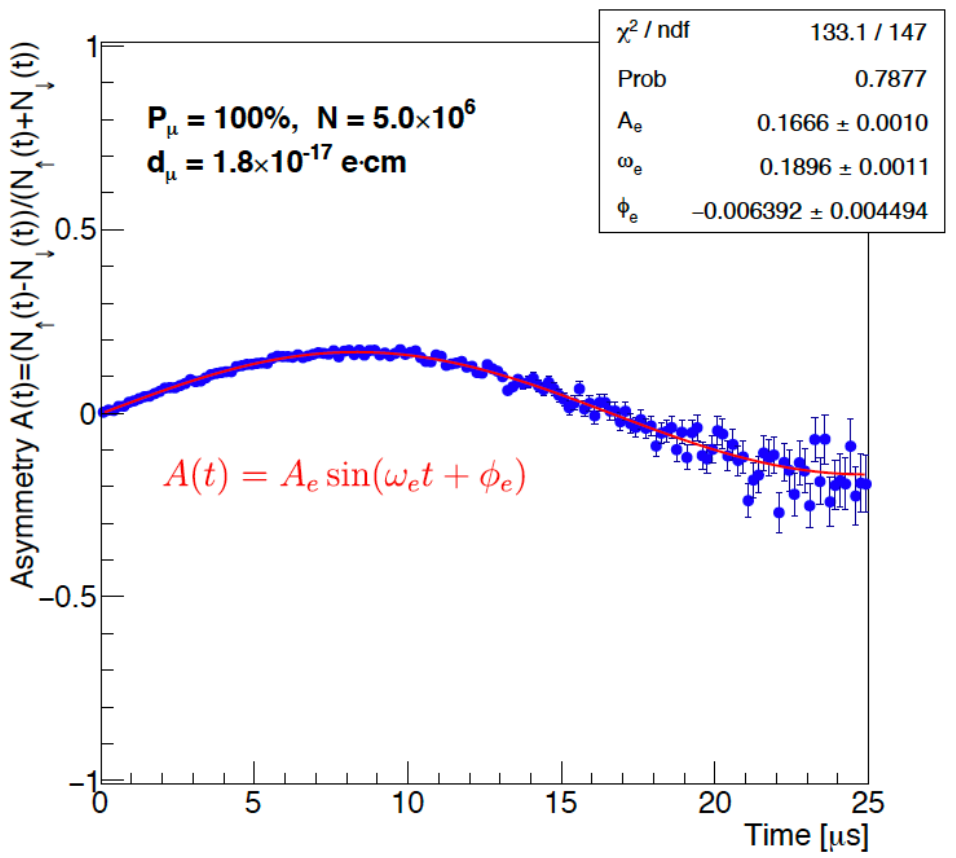


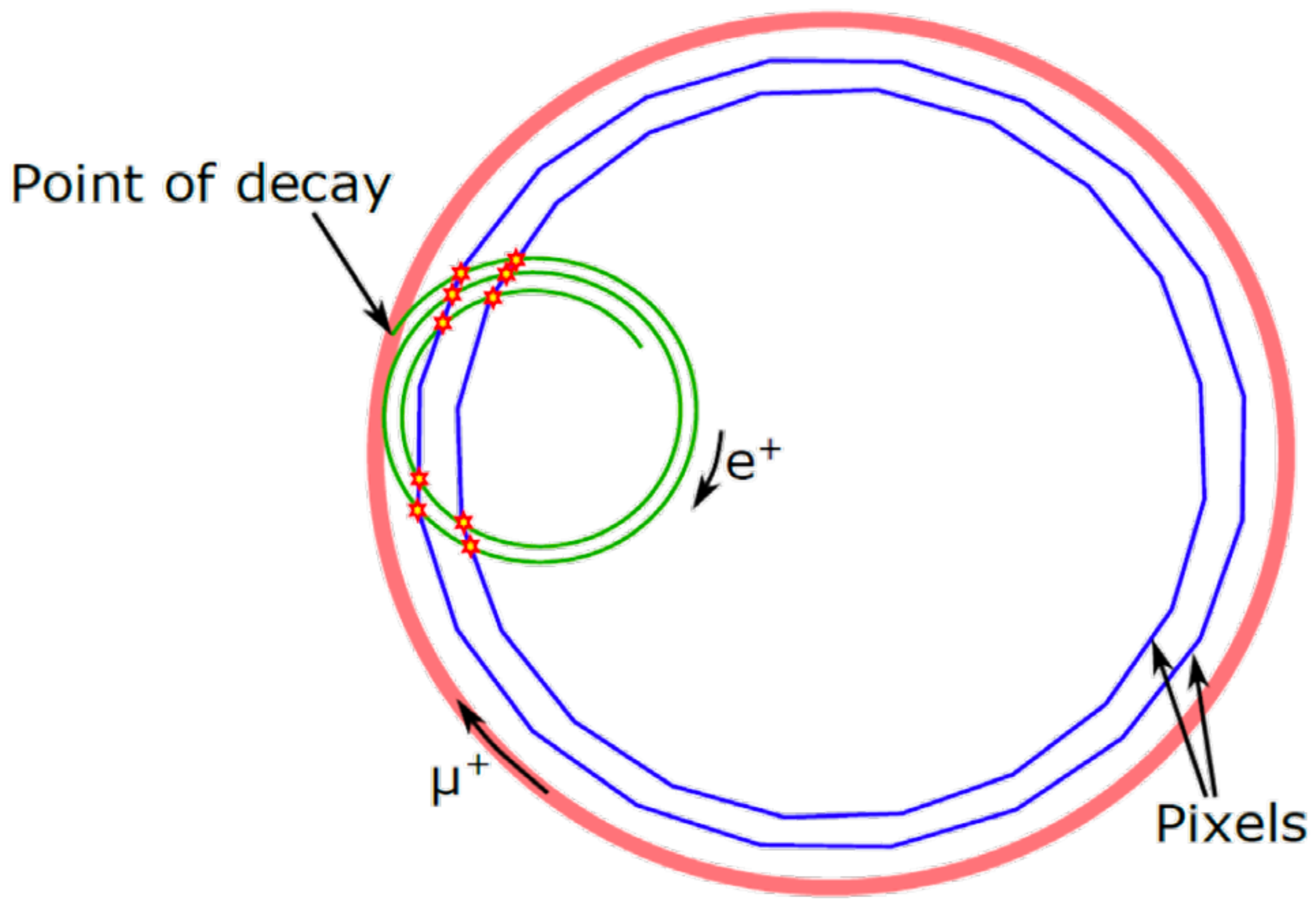
Positron trackers for EDM measurement

- Current considerations:
  - Barrel detector made of pixelated HV-MAPS silicon sensors
  - Fast exit signal by scintillators (e.g. fibers) to lift veto for next muon entrance (one muon at a time measurement)



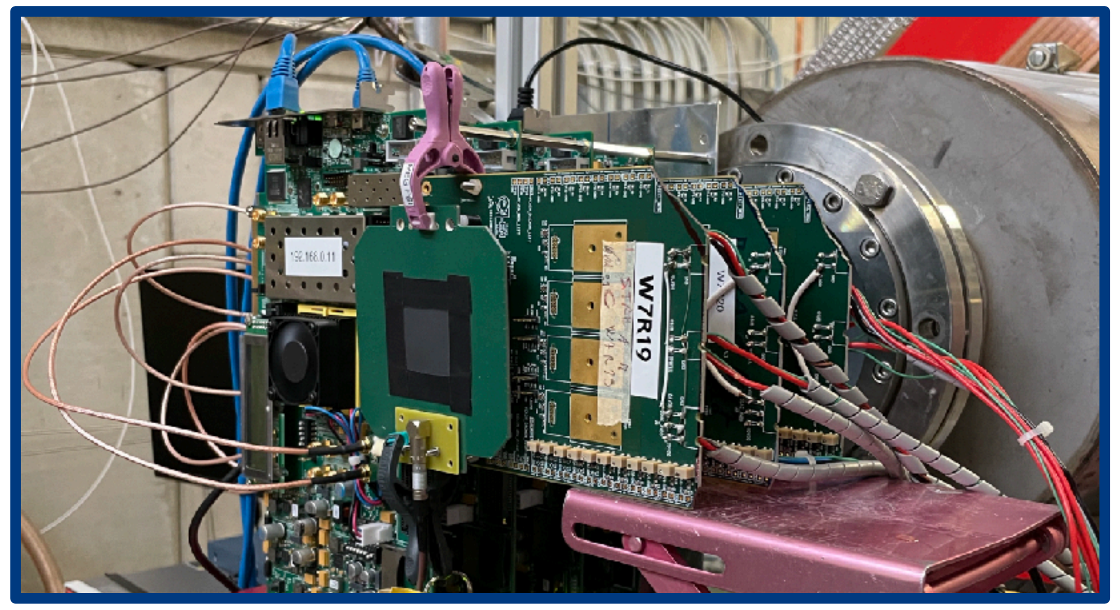


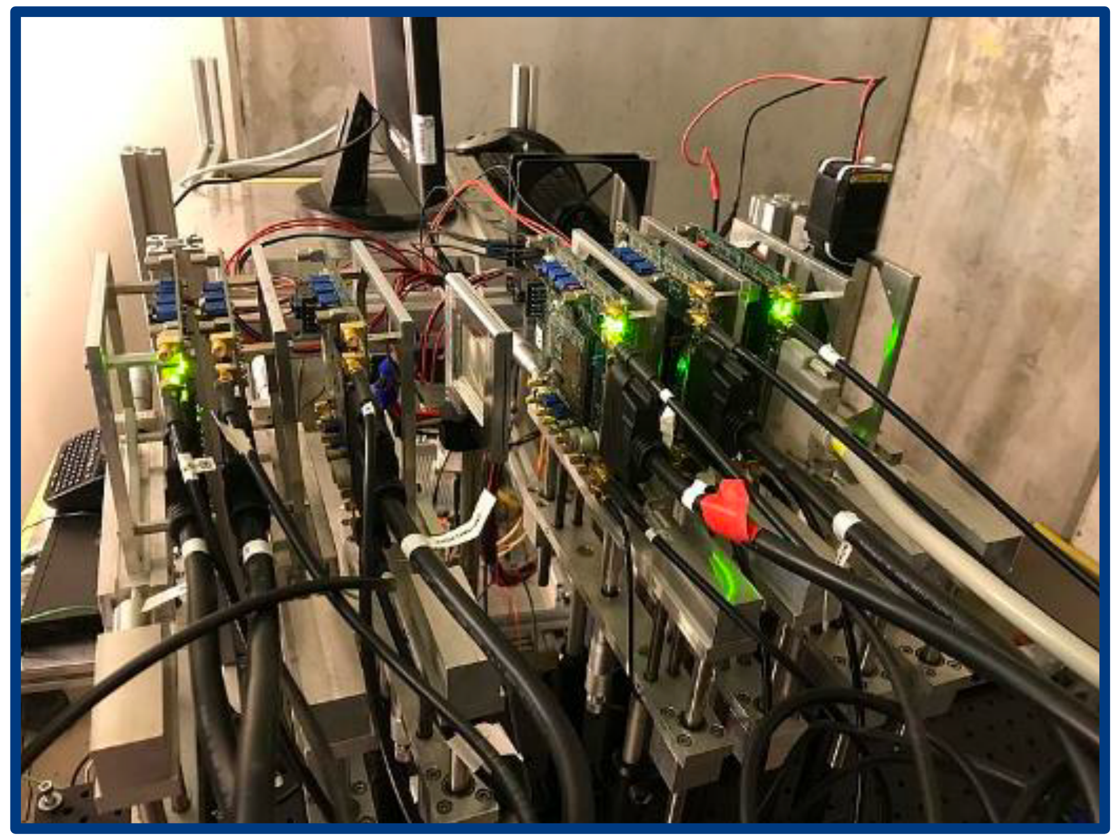


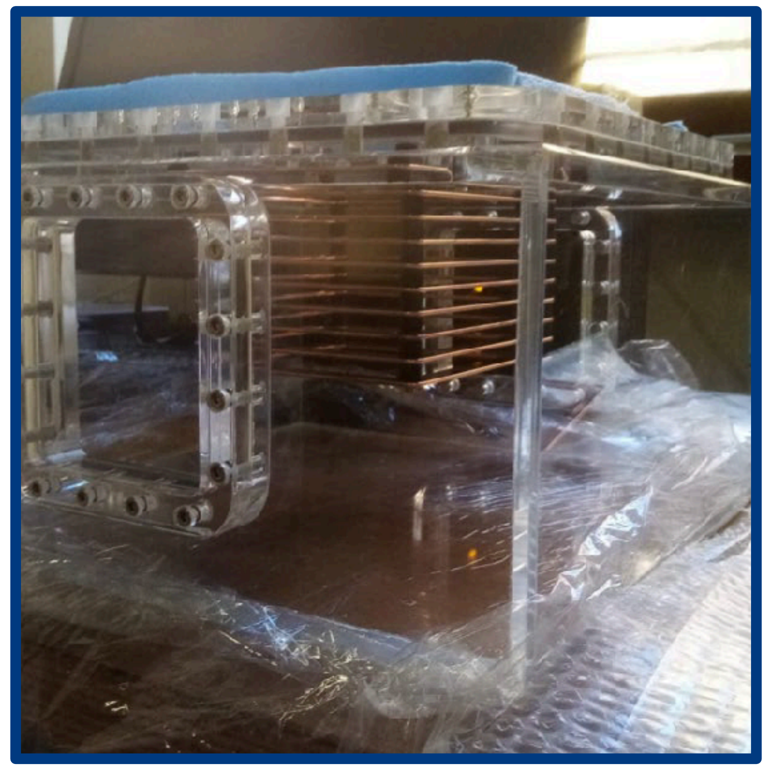


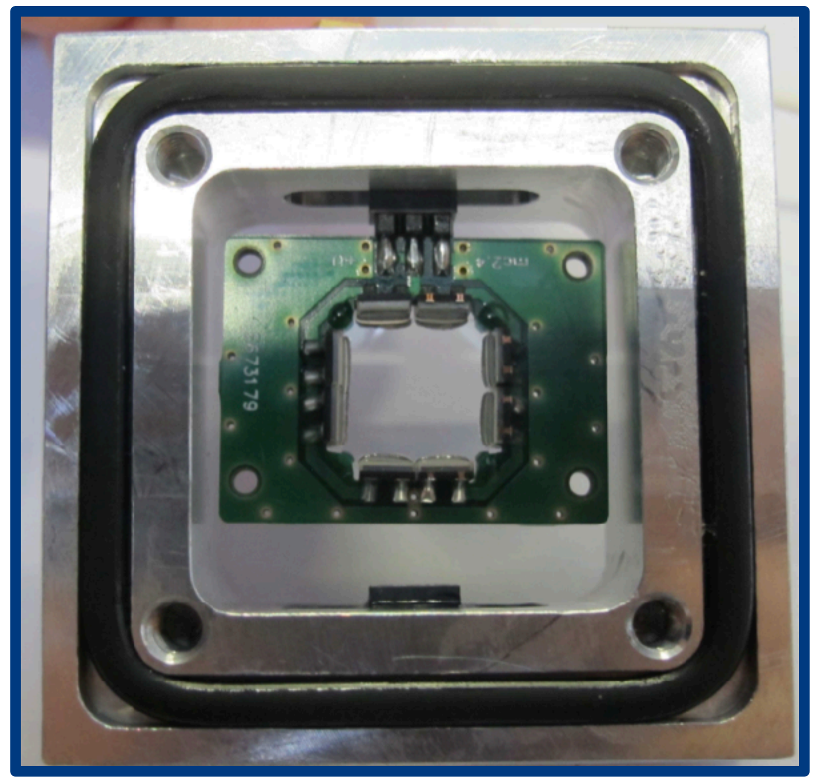
Annual beam tests at PSI

- 2019
  - Characterization of potential beam lines
- 2020
  - Study multiple scattering of positrons at low momenta
- 2021
  - Characterization of potential electrode material with positrons and muons
- 2022
  - Performance test of entrance/collimating channel
  - Performance test of TPC muon tagger/tracker









Beam measurement at πE1/μE1 (BT 2019)

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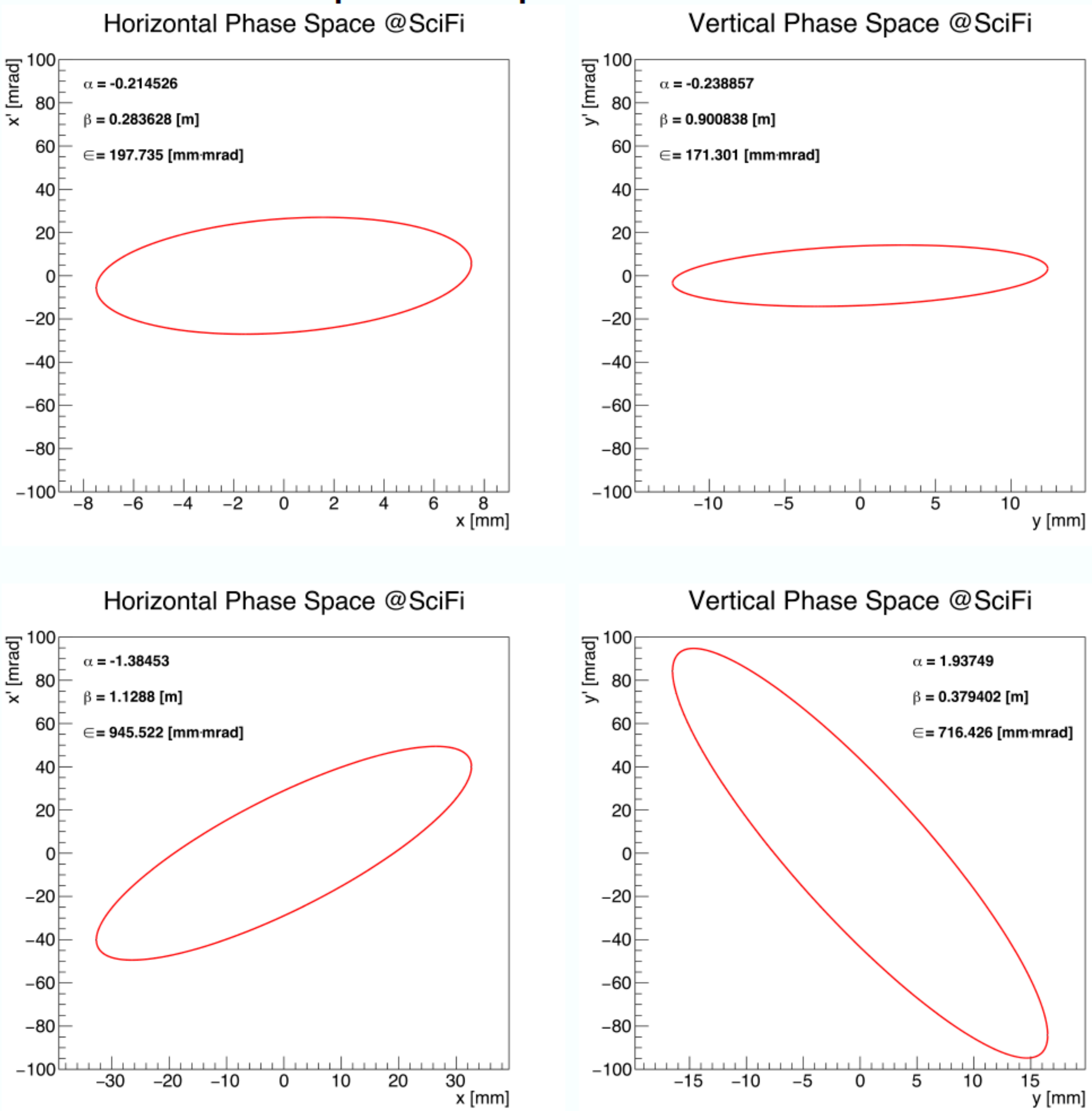
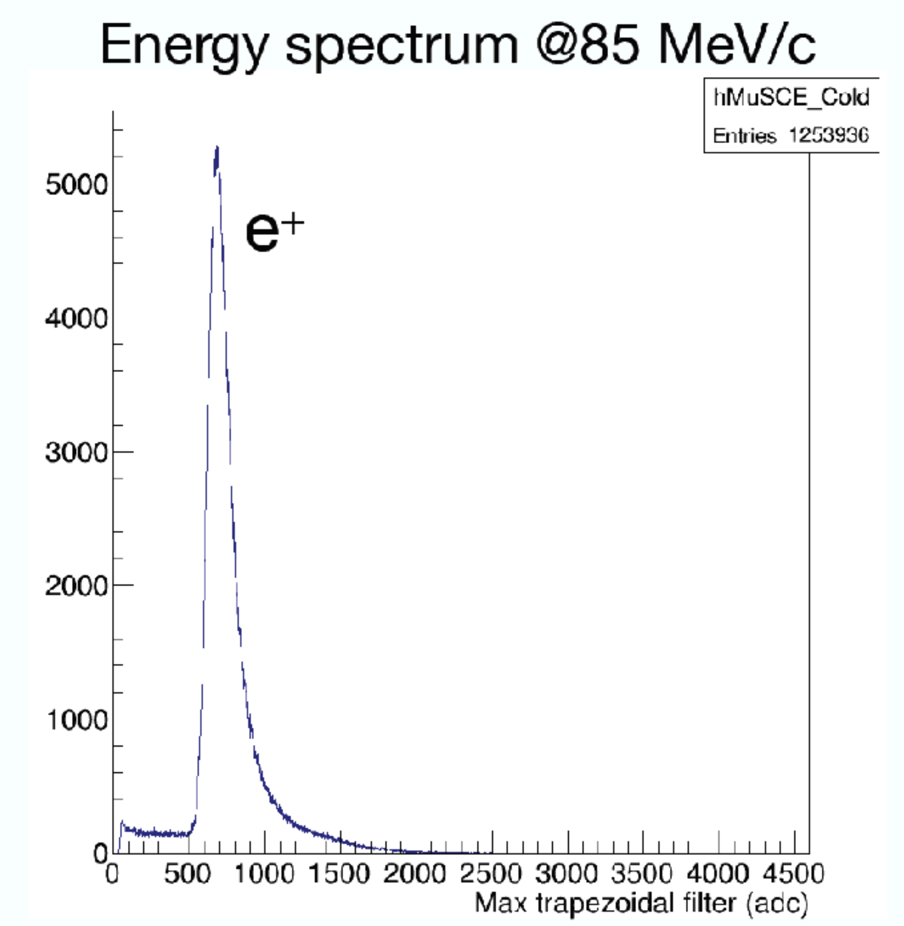
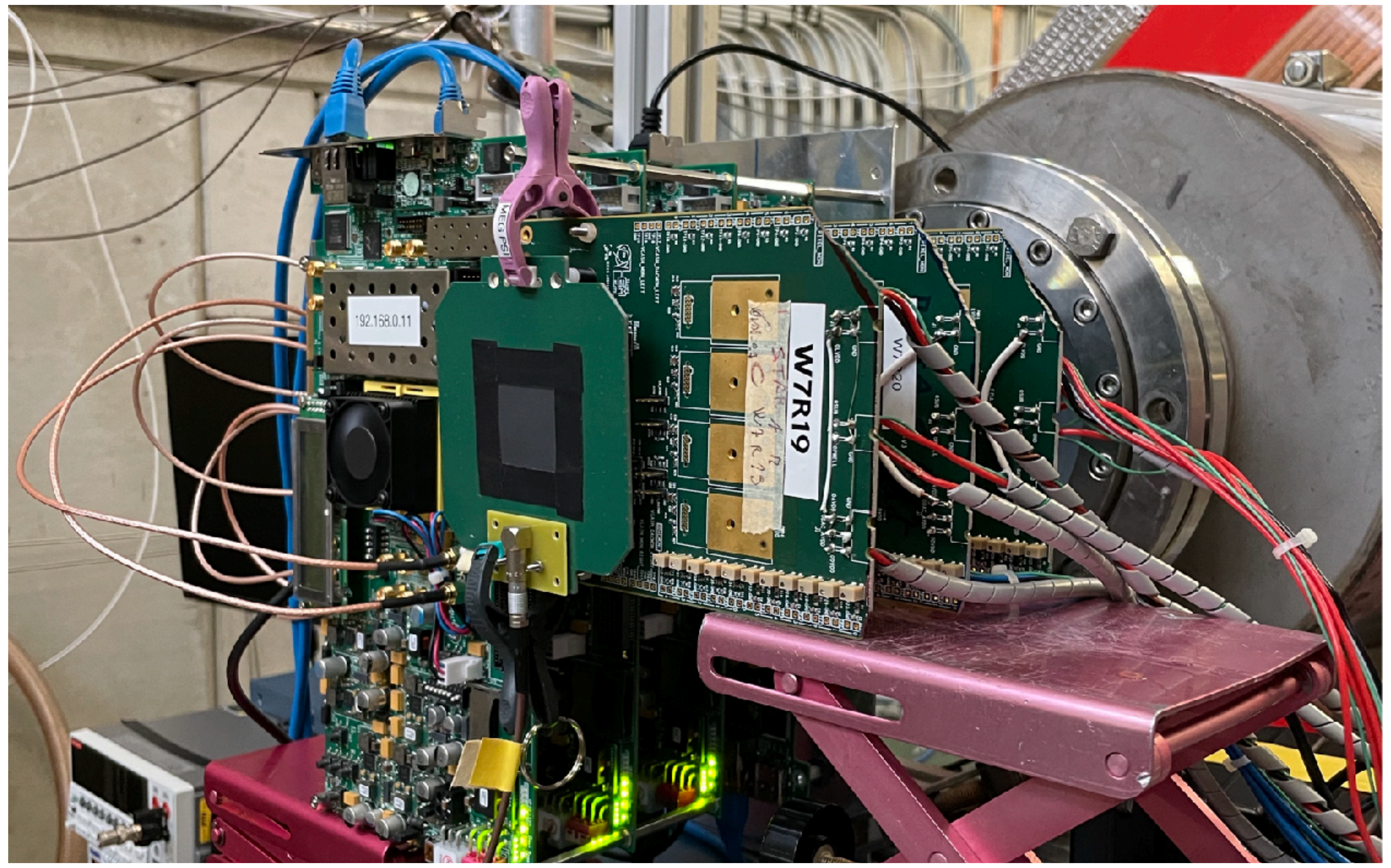
- Quadrupole scan technique was used to determine phase space
- πE1 @28 MeV/c (Precursor)
  - R_μ up to 6.6×10^6 μ^+/s @2.4 mA
  - Emittance (1σ)
    H: 198 mm•mrad
    V: 171 mm•mrad
- μE1 @125 MeV/c (Final data taking)
  - R_μ up to 1.2×10^8 μ^+/s @2.4 mA
  - Emittance (1σ)
    H: 945 mm•mrad
    V: 716 mm•mrad
  - P ~ 93%

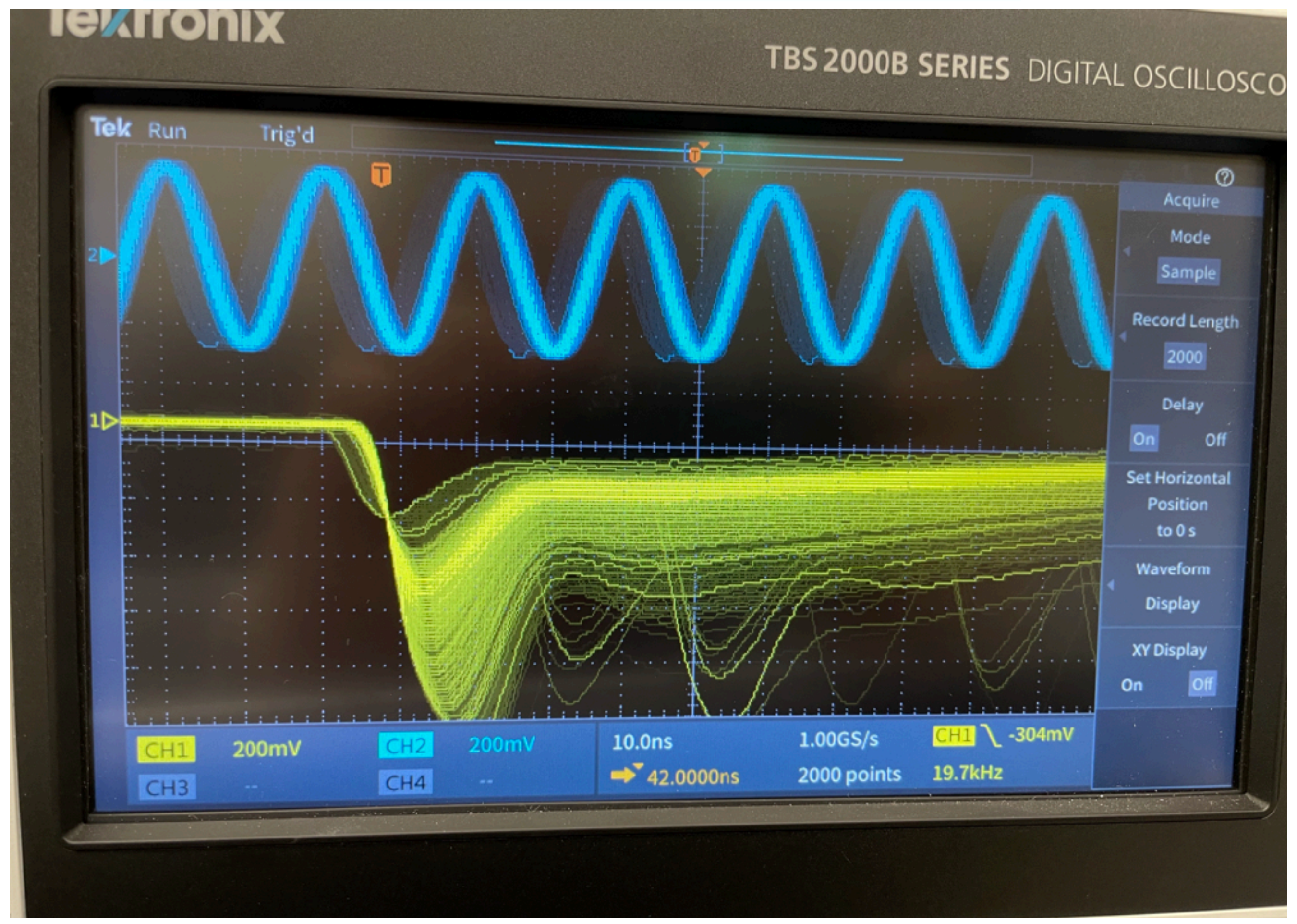


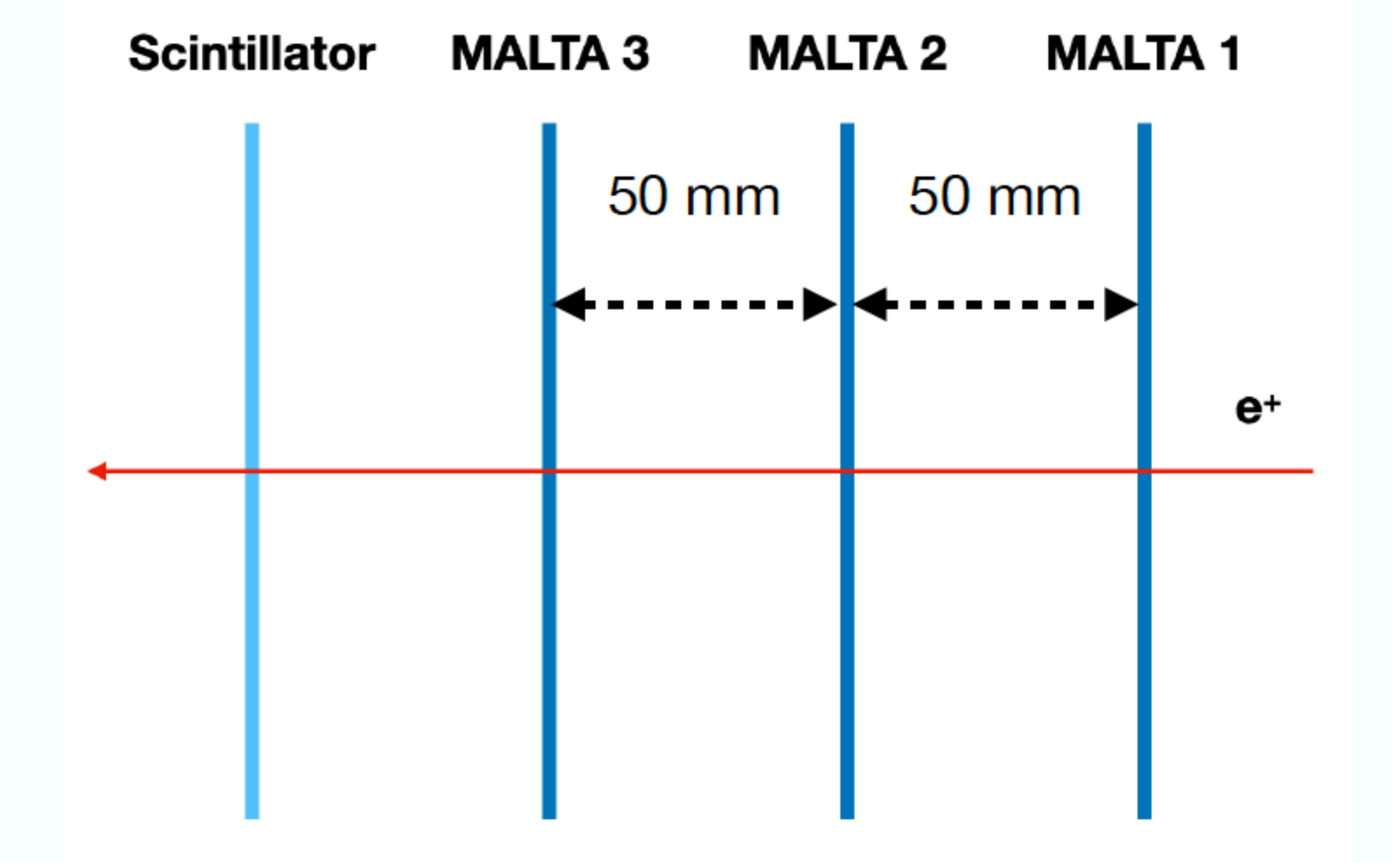
Study of multiple scattering (BT 2020)

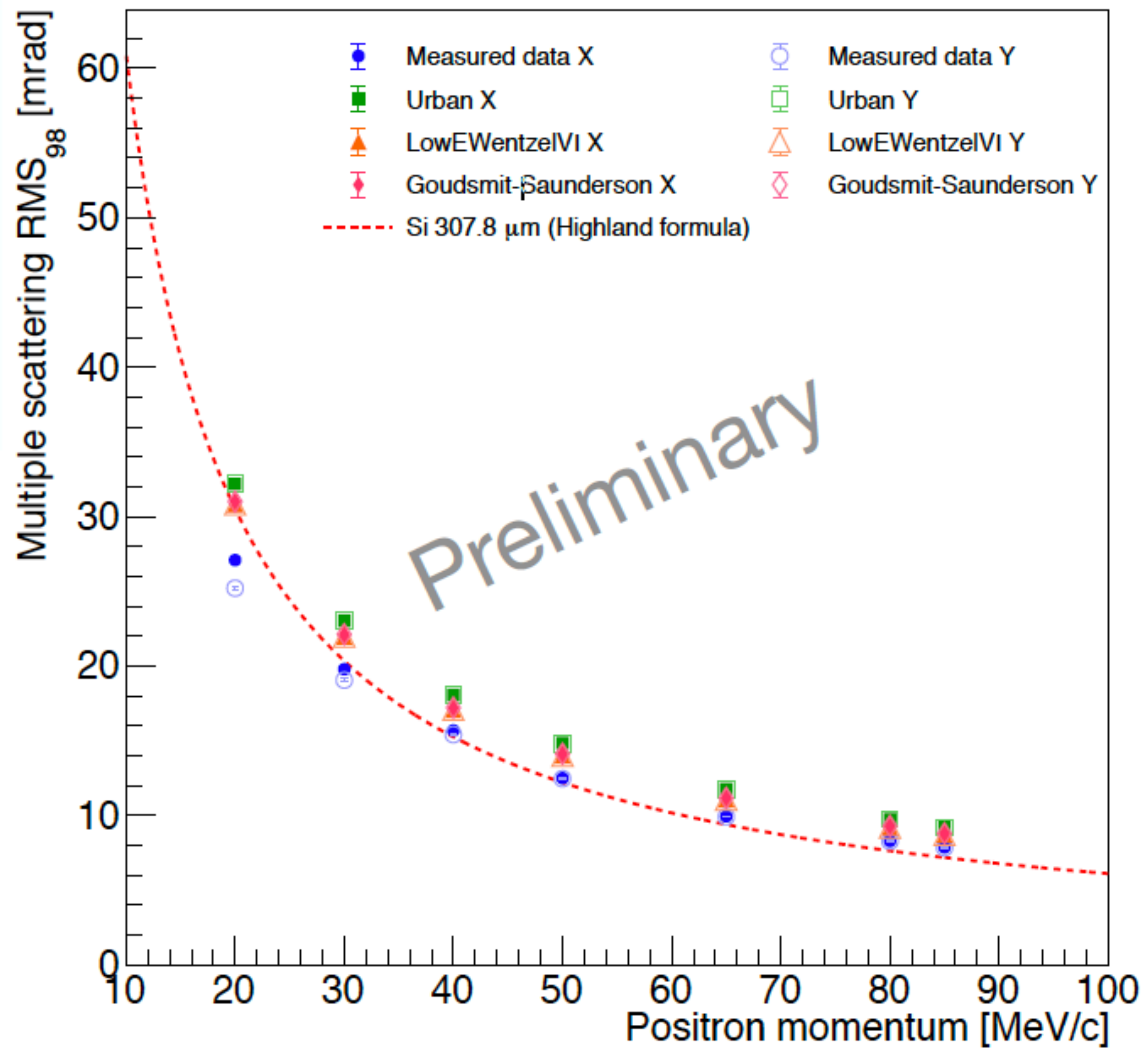
- Study multiple scattering of positrons at low momenta with using 3-plane MALTA telescope
  - Matrix of 512 × 512 pixels
  - Pixels of 36.4 × 36.4 μm2
  - sensor thickness: ~300 μm
- e+: 20 — 85 MeV/c
- Tested 2 configurations:
  → MALTA as active target
  → MALTA + Kapton/Mylar







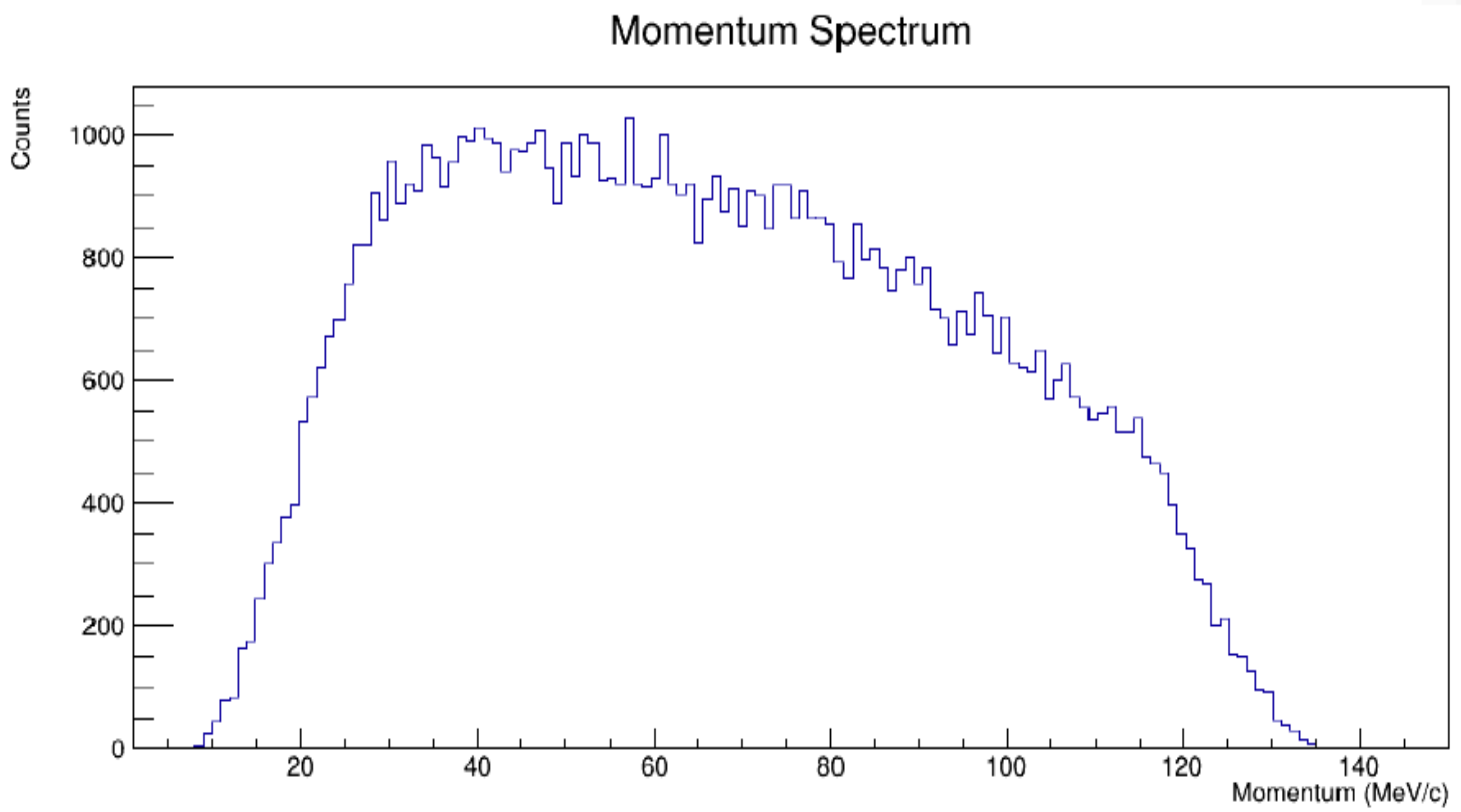


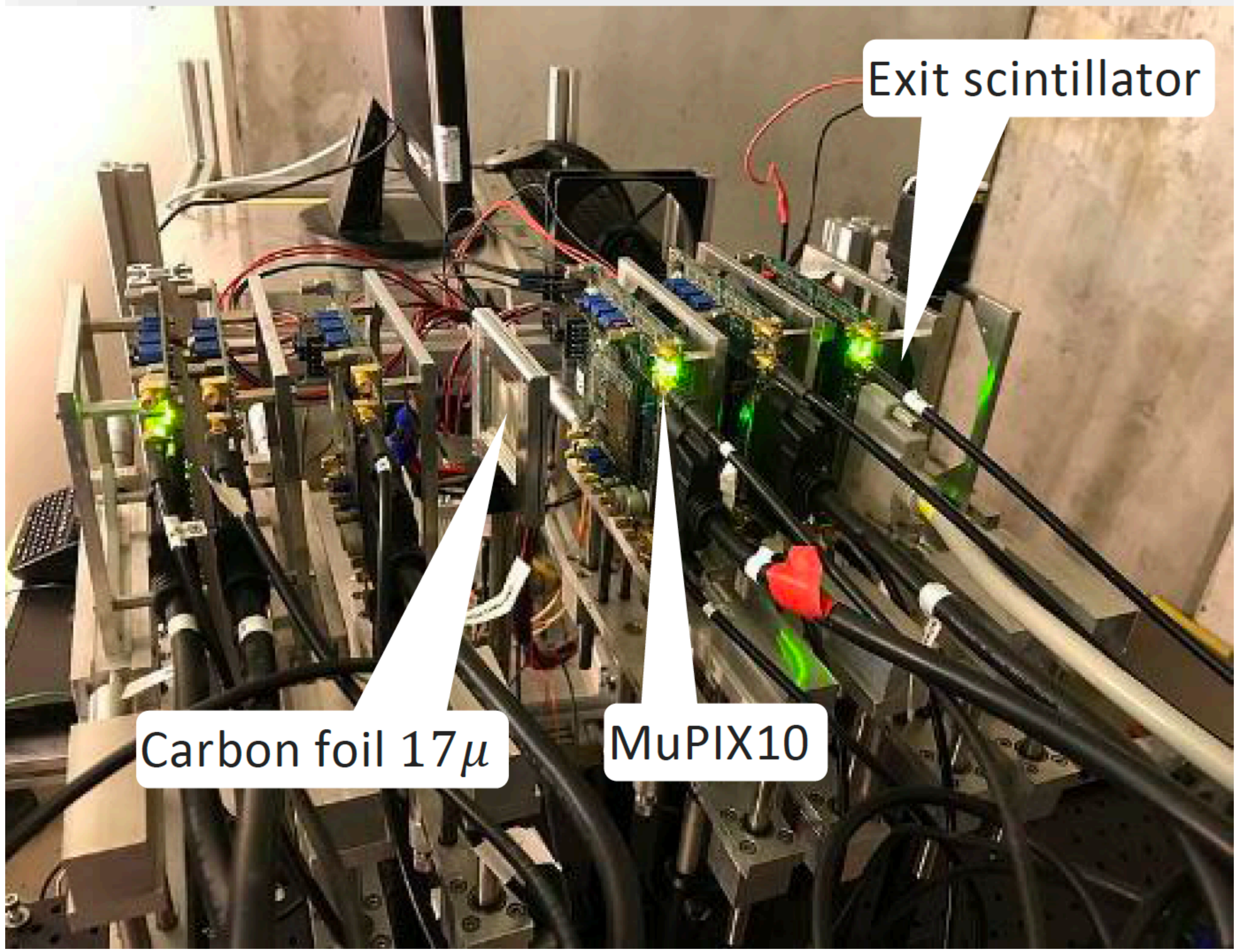


Screening electrode materials (BT 2021)

- Characterization of potential electrode material with positrons and muons

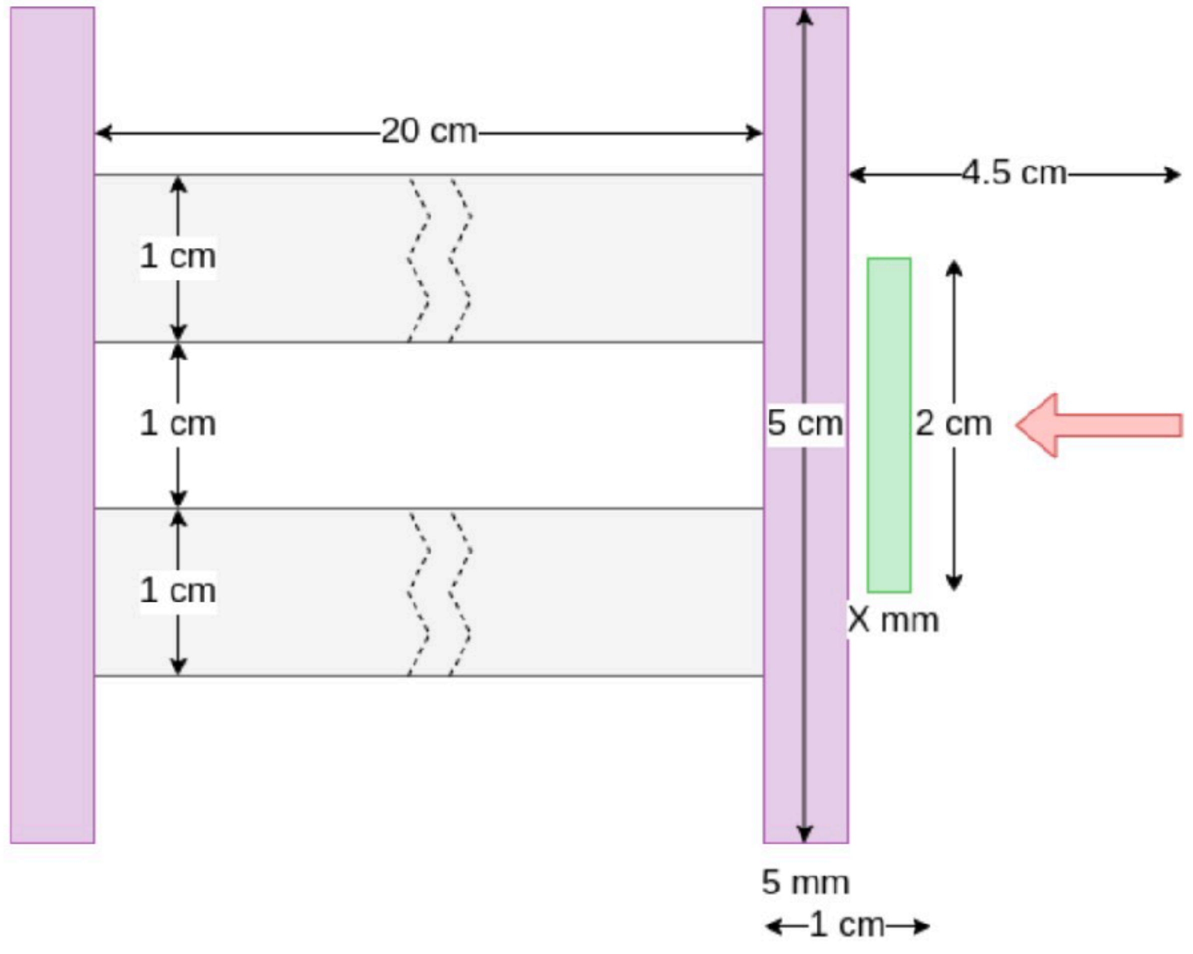
$$50\ \mathrm{MeV}/c < p < 145\ \mathrm{MeV}/c$$

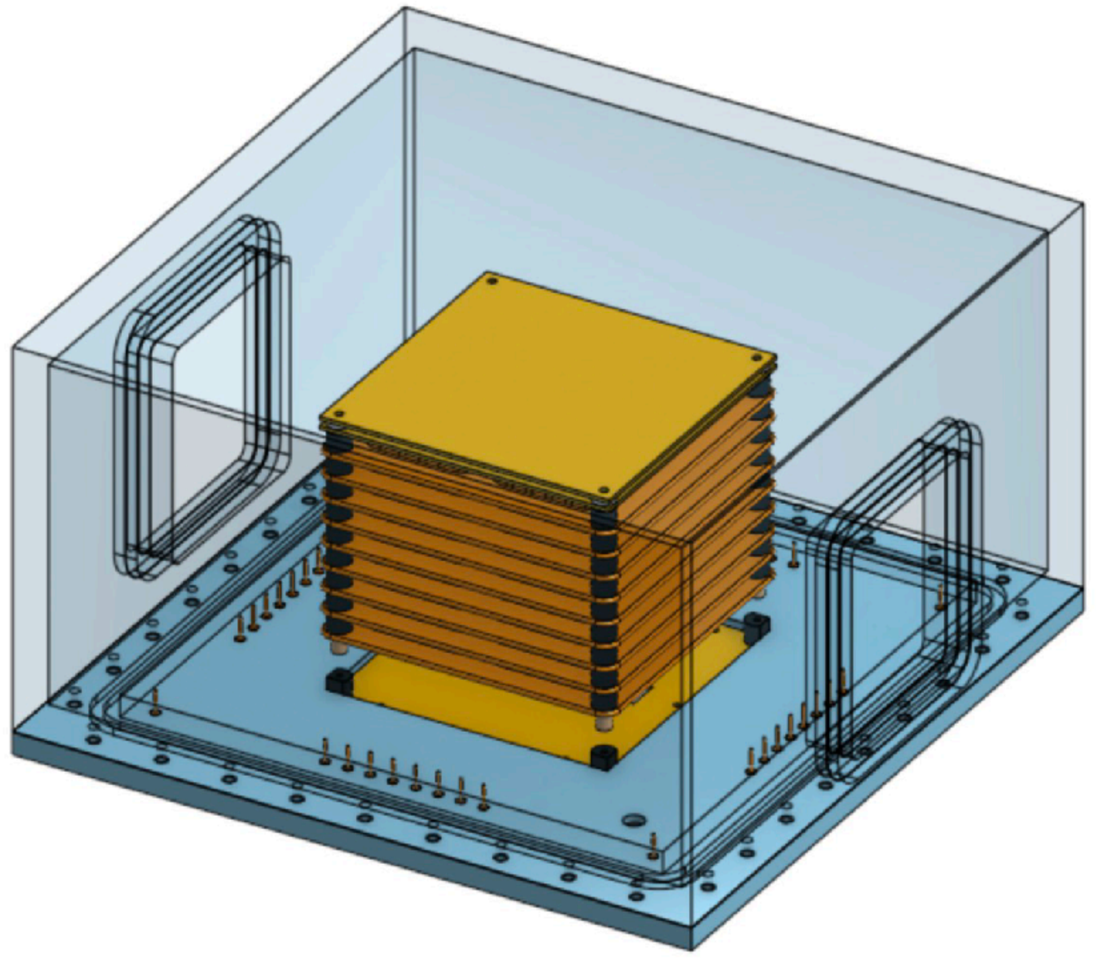


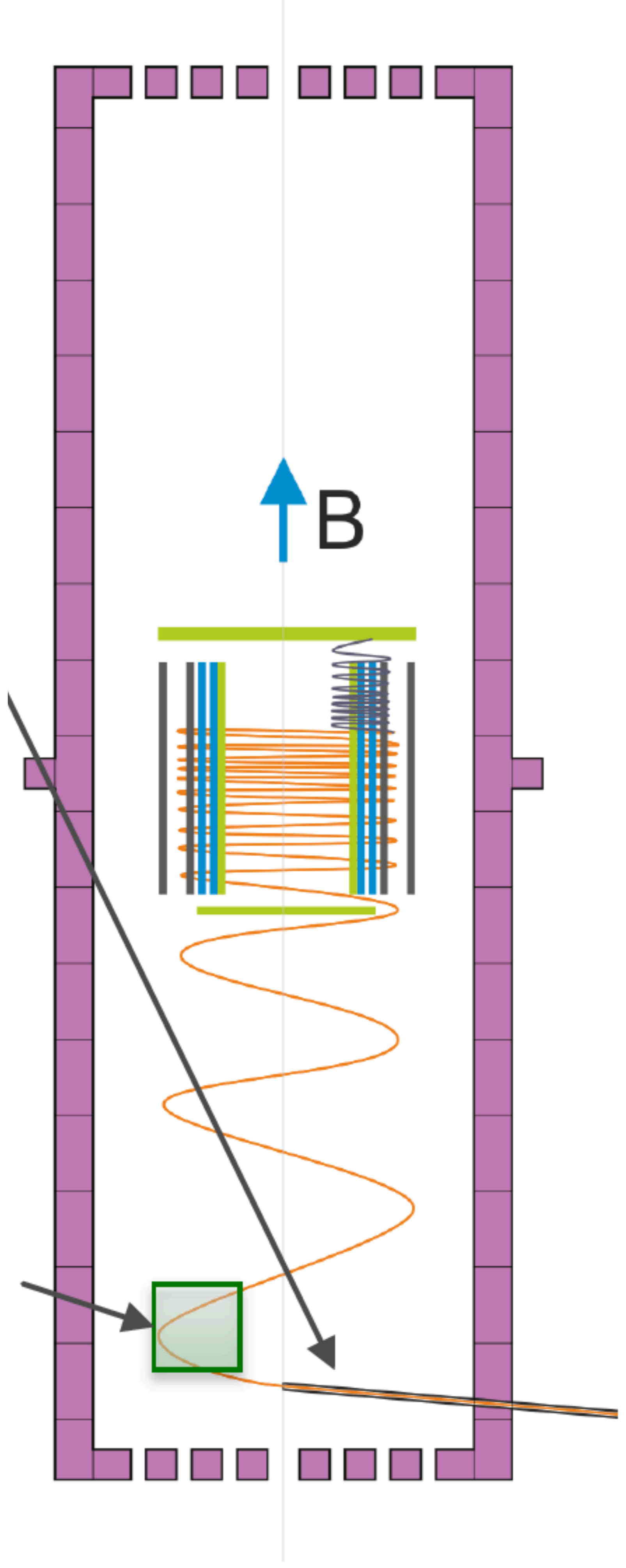


Beam time @ PSI in 2022

- Muon tagger/tracker (done in June!)
  - Track resolution
  - Multiple scattering on gas and windows
- Muon entrance detector
  - Collimation efficiency
  - Thickness to minimize multiple scattering while having enough light yield
  - Specular reflections on scintillators

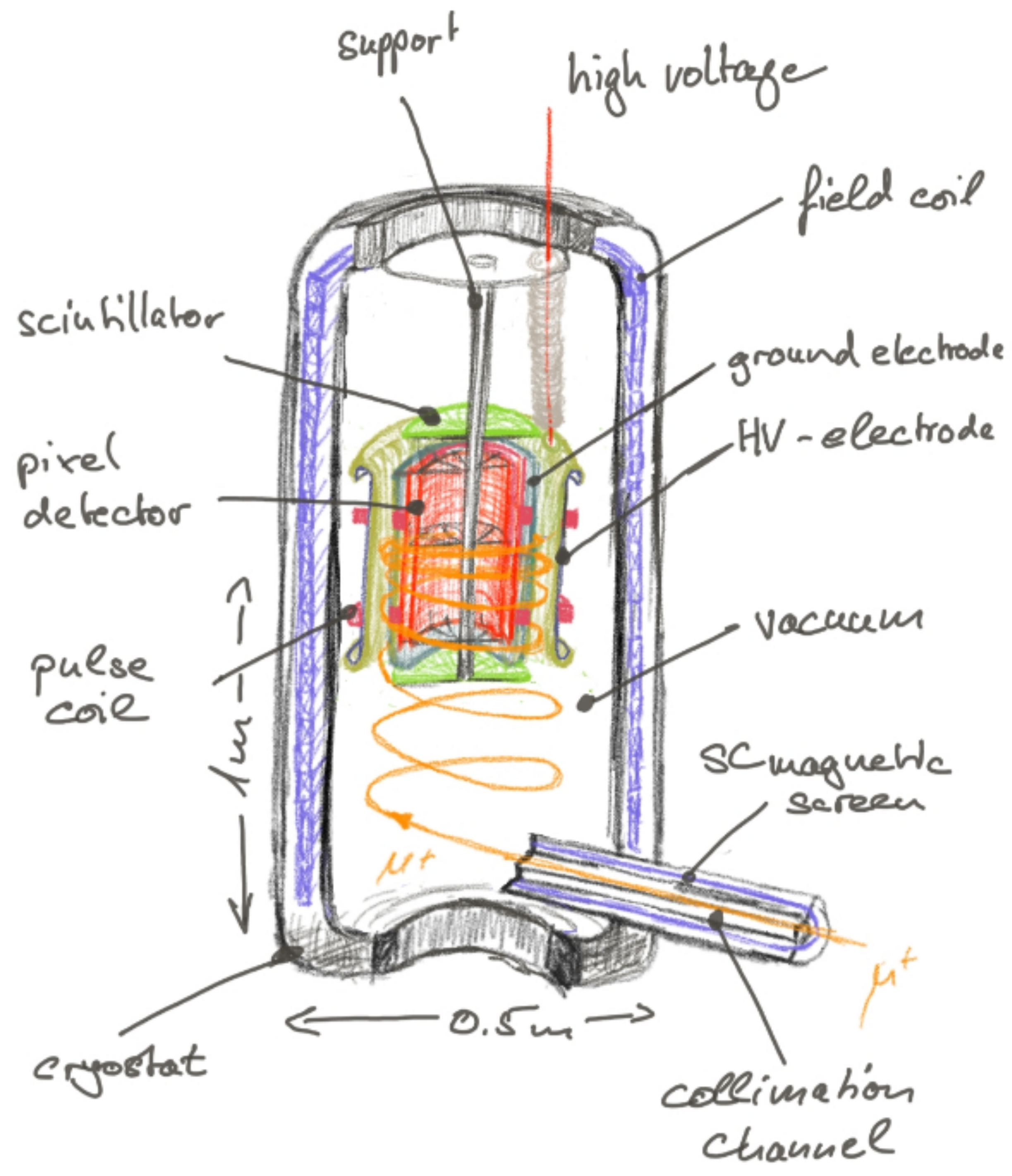






Projected Final Sensitivity of 10^{-23} e cm

Key parameters	Symbols	Phase 1 @ 28 MeV/c	Phase 2 @ 125 MeV/c
Muon beam rate		$2 \times 10^{6}\ s^{-1}$	$1.2 \times 10^{8}\ s^{-1}$
After collimation		$1 \times 10^{6}\ s^{-1}$ (ε=50%)	$1.2 \times 10^{8}\ s^{-1}$ (ε=0.5%)
After beam injection		3 kHz (ε=0.3%)	480 kHz (ε=60%)
Gamma factor	γ	1.03	1.77
Initial polarization	P	0.95	0.95
Electric field	E_r	0.3 MV/m	2 MV/m
Positron detection rate		0.5 kHz	80 kHz
Muon decay asymmetry	α	0.3	0.3
Detections (200 days)	N	4×10^{11}	10^{12}
Sensitivity		**< 3×10^{-21} e cm**	**< 6×10^{-23} e cm**



$$\sigma(d_\mu) = \frac{\hbar \gamma^2 a_\mu}{2 P E_f \sqrt{N}\, \gamma \tau_\mu\, \alpha}$$

Potential systematic effects

- Systematics: all effects that lead to the real or apparent precession of the spin mimicking EDM signal
- BNL/FNAL EDM searches provided very good guidance:
  - Misalignment in fields and detectors
  - Variation in detection efficiency
  - New type of systematics inclusively for frozen-spin approach
- Derive specifications of all technical designs of the experiment
  - Careful analysis of systematics using toyMC and Geant4 simulations

Growing collaboration!

李政道研究所 TSUNG-DAO LEE INSTITUTE

selected for funding, funded by SBFI

European Research Council

The muEDM – collaboration

Fonds national suisse

- A. Adelmann,[1,2] M. Backhaus,[1] C. Chavez Barajas,[3] N. Berger,[4] T. Bowcock,[3] A. Bravar,[5] C. Calzolaio,[2] L. Caminada,[2,6] G. Cavoto,[7] R. Chislett,[9] A. Crivellin,[2,6,10] C. Dutsov,[2] M. Daum,[2] M. Fertl,[11] M. Giovannozzi,[10] W.C. Griffith,[12] G. Hiller,[13] G. Hesketh,[9] M. Hildebrandt,[2] T. Hume,[2] A. Keshavarzi,[14] K.S. Khaw,[16,17] K. Kirch,[1,2] A. Kozlinsky,[4] A. Knecht,[2] M. Lancaster,[15] B. Märkisch,[18] F. Meier Aeschbacher,[2] F. Méot,[19] A. Papa,[2,20] J. Price,[3] F. Renga,[7,8] M. Sakurai,[1] P. Schmidt-Wellenburg,[2] M. Schott,[4,11] T. Teubner,[3] C. Voena,[7,8] J. Vossebeld,[3] and F. Wauters[4]

1 ETH

2 PAUL SCHERRER INSTITUT PSI

3 UNIVERSITY OF LIVERPOOL

4 JG|U

5 UNIVERSITÉ DE GENÈVE

6 University of Zurich UZH

7 SAPIENZA UNIVERSITÀ DI ROMA

8 INFN Istituto Nazionale di Fisica Nucleare

9 UCL

10 CERN

11 Cluster of Excellence PRISMA+

12 US University of Sussex

13 tu technische universität dortmund

15 MANCHESTER 1824 The University of Manchester

16 上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

17 李政道研究所 Tsung-Dao Lee Institute

18 TUM

19 BROOKHAVEN NATIONAL LABORATORY "a passion for discovery"

20 UNIVERSITÀ DI PISA

NSFC 国家自然科学基金委员会 National Natural Science Foundation of China

Collaboration activities

Kick-off workshop for the search of a muon EDM using the frozen spin technique at PSI

Feb 17, 2020, 9:00 AM → Feb 19, 2020, 5:00 PM Europe/Zurich

Mikio Sakurai (ETH Zürich), Philipp Schmidt-Wellenburg (Paul Scherrer Institut), Anita Van Loon (Paul Scherrer Institut)

Description: Mailing List: https://elog.psi.ch/elogs/Muon+EDM+Mailing+List/

Remote link: https://psi-ch.webex.com/psi-ch/j.php?MTID=mbb1db2d988c4d00d68ec5da10b33ad15 (Muon2020)

The aim of the workshop is to bring together scientists strongly motivated to participate in a search for a muon electric dipole moment (EDM) using the frozen spin technique at PSI.

The workshop will be organized as a topical seminar with break-out sessions addressing the different challenges of a compact muon storage ring employing the frozen spin technique to search for an electric dipole moment of the muon. In addition to invited contributions (30'), we very much appreciate shorter contributions by all participants. We plan for ample discussion time in each session.

muEDM Collaboration Meeting October 2021

Oct 7, 2021, 9:30 AM → Oct 8, 2021, 12:00 PM Europe/Zurich

Description: Principle goal for the meeting: Decision on proposal submission

Start of meeting: October 7, 9h30
End of meeting: October 8, 12h00
Zoom: Online Meeting

muEDM Workshop Pisa, May 2022

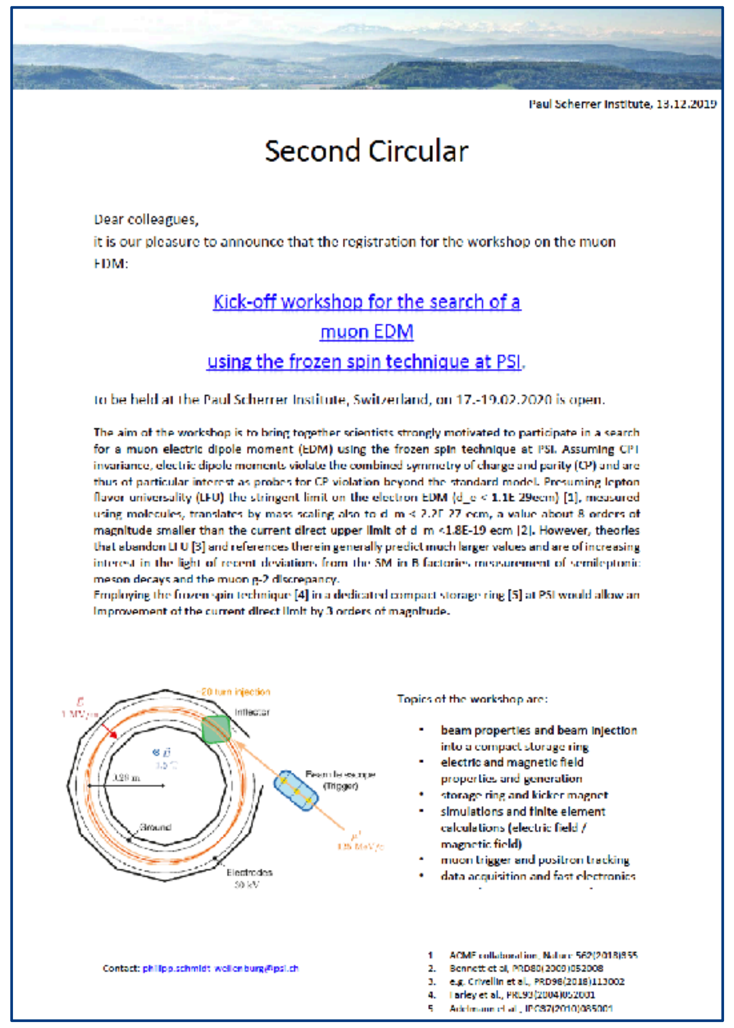
12 May 2022, 14:00 → 13 May 2022, 17:15 Europe/Zurich

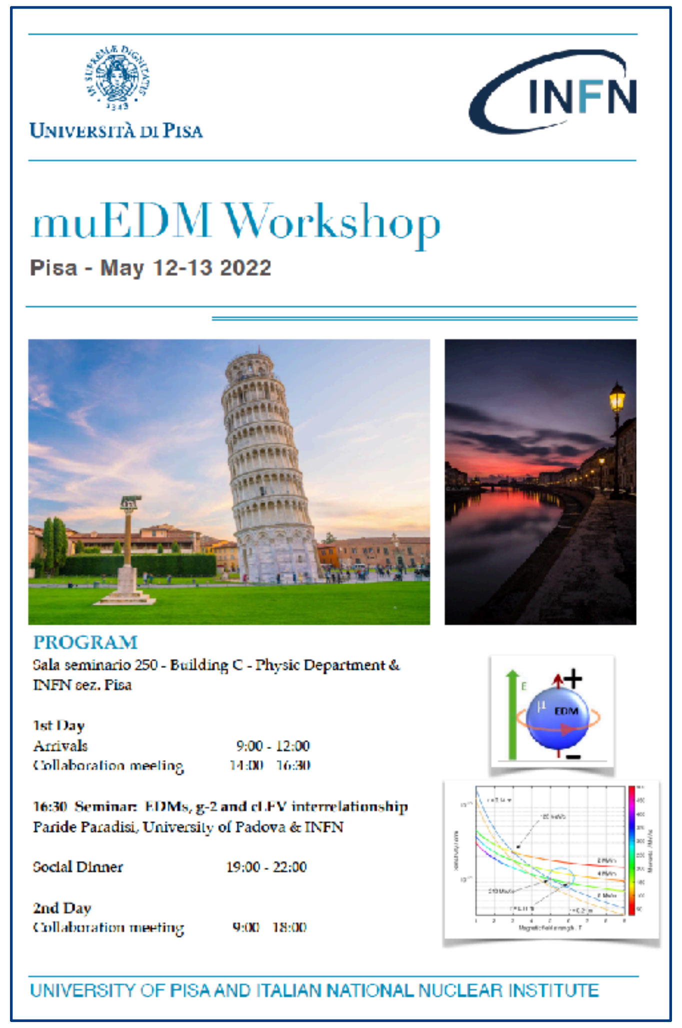
250 (Dipartimento di Fisica&INFN)

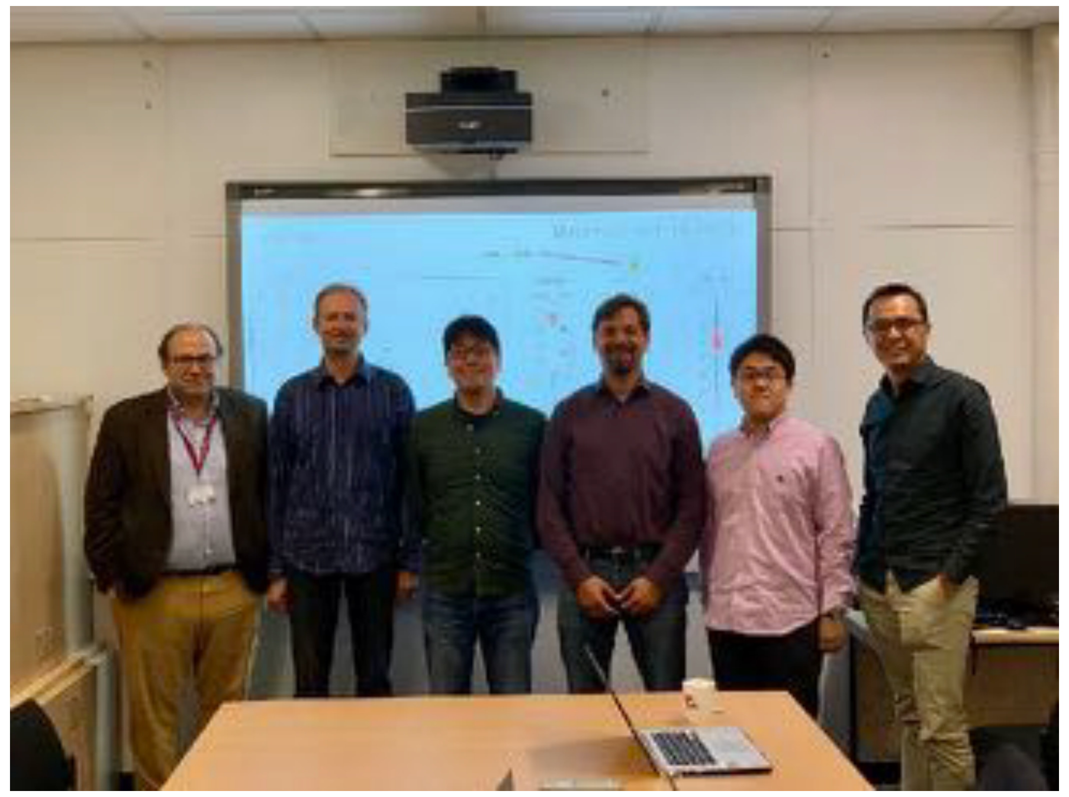
Hotel list.pdf | muEDM_Pisameeti... | Short_PisaGuide.pdf | Zoom link for remot...

Registration: Participants — Register

Angela Papa: angela.papa@unipi.it, angela.papa@psi.ch, +393491567235







+ monthly meetings and online collaboration meetings in between

Collaboration Organization

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Making good progress in collaboration strategy in realizing the experiment!

- **Magnetic field**
  - Pulse coil
  - Adjustment coils
  - Field free injection channel
  - Field mapping
  - B-Field monitor
- **Electric field**
  - Electrodes
  - Feedthrough
  - E-field measurement
- **Mechanical setup**
  - Electrode / detector rig
  - Support SC channel
  - CAD model
  - Vacuum
  - PSC rotation table
  - PSC vertical adjustment
- **Cryogenics**
  - Cooling device
  - 70 K shield
  - 4K layout
- **Particle detection**
  - Muon entrance trigger
  - Positron g-2 detection
  - Positron EDM detector
- **Beam line**
  - MC Start to stop
  - Luminosity optimization
  - Injection
- **DAQ / Electronics**
  - Muon trigger generation
  - Positron DAQ
  - Pulser / current pathes
  - Environmental parameters
  - Data storage
- **Analysis**
  - Systematic effects
  - Toy MC
  - MC framework
  - FEM field model
  - Code repository GIT

Schedule and milestone

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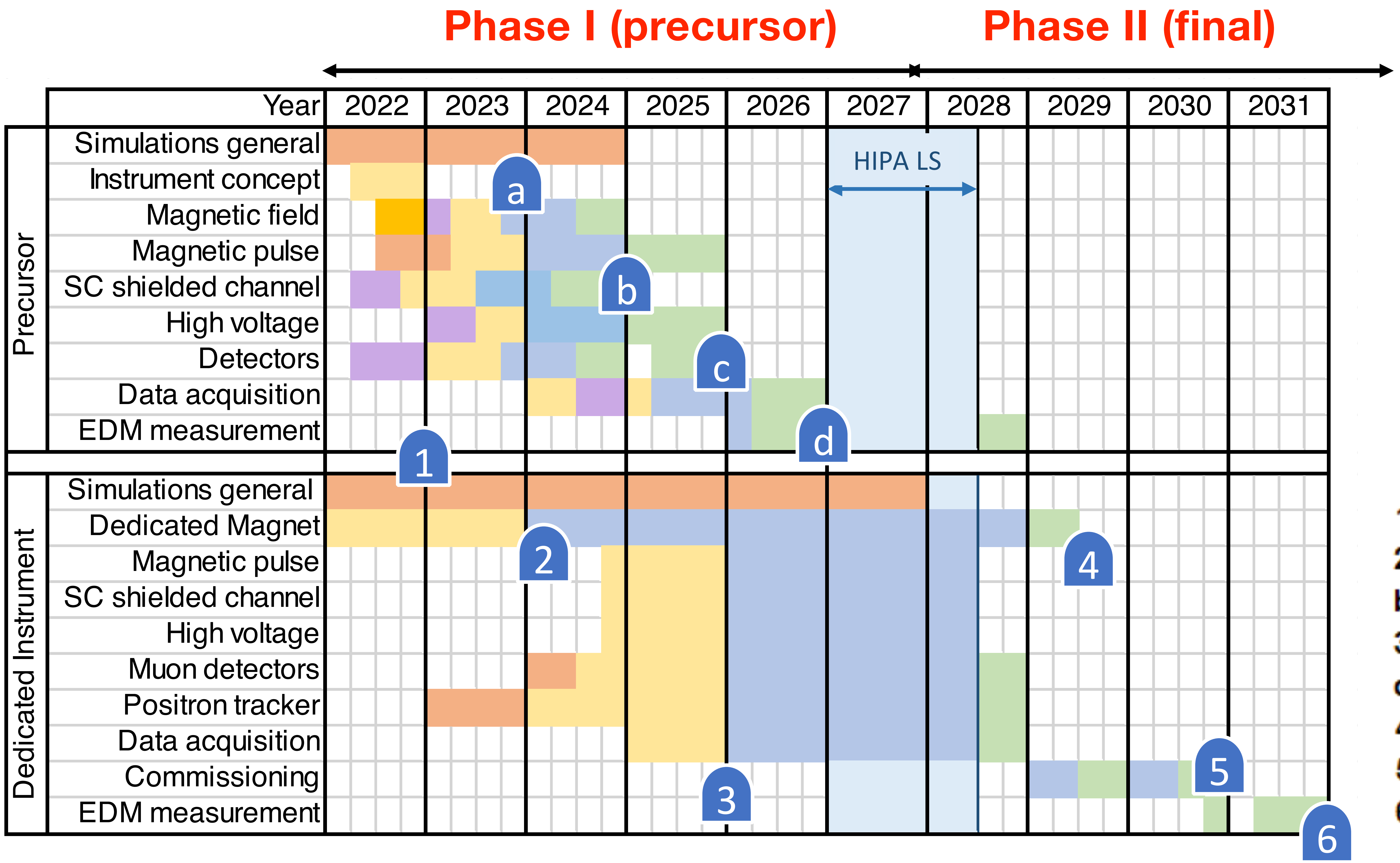


Simulations	
Conception/Design	
Prototyping	
Acquisition/Assembly	
Tests/Measurements	

1	Full proposal for both phases to CHRISP committee
2/a	Magnet call for tender / precursor design fix
b	Precursor ready for assembly/commissioning
3/c	Technical design report / frozen spin demonstration
d	First data for precursor muEDM
4	Magnet delivered, characterized and accepted
5	Successful commissioning / start of data taking
6	End of data acquistion for muEDM

Muonphilic dark matter

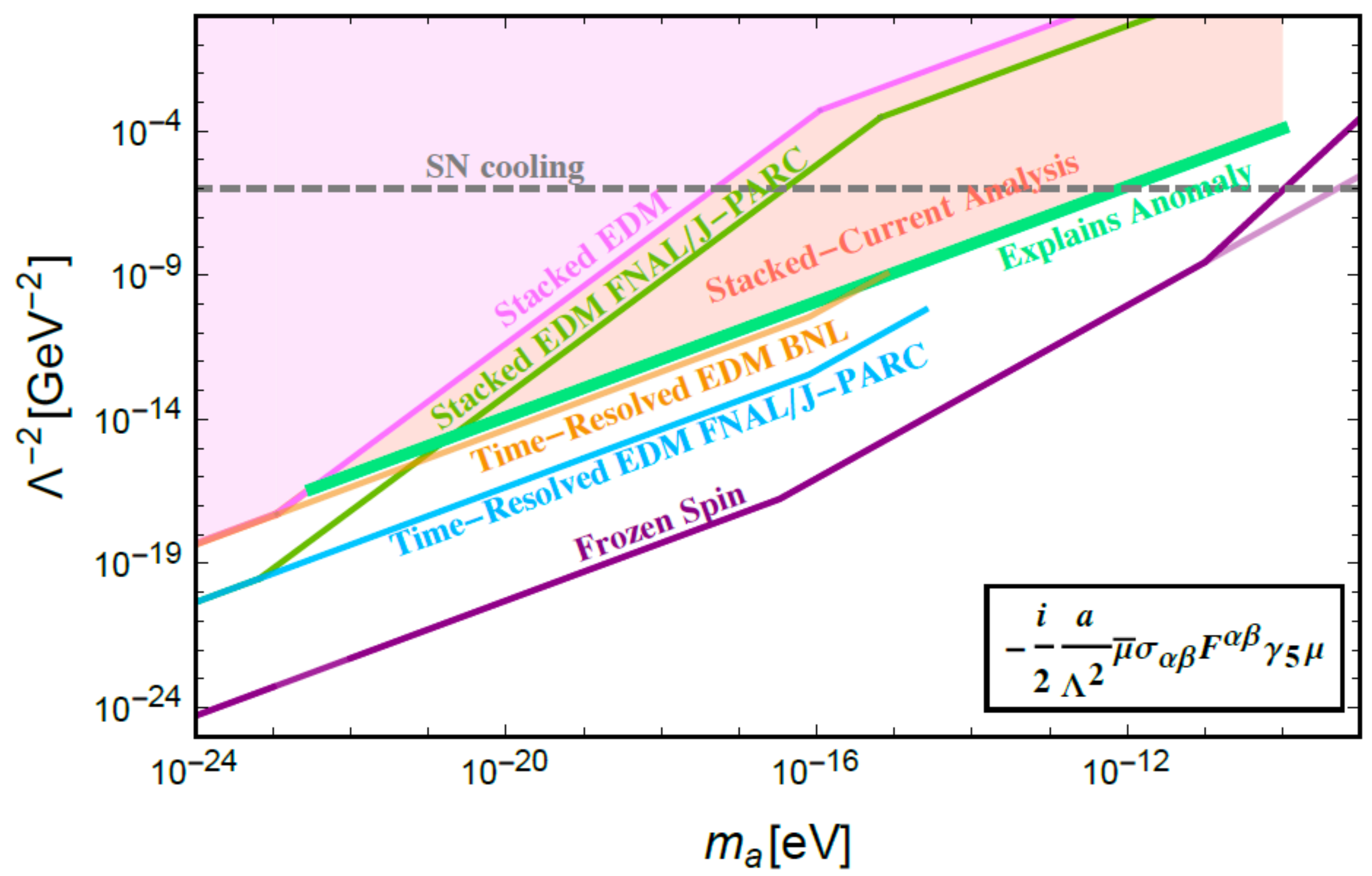
PHYSICAL REVIEW D **102,** 115018 (2020)

Muon g-2 and EDM experiments as muonic dark matter detectors

Ryan Janish[1,2] and Harikrishnan Ramani[1,3,4]

[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
[2]*Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[3]*Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4]*Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*

Detection Reach for Muon EDM Coupling



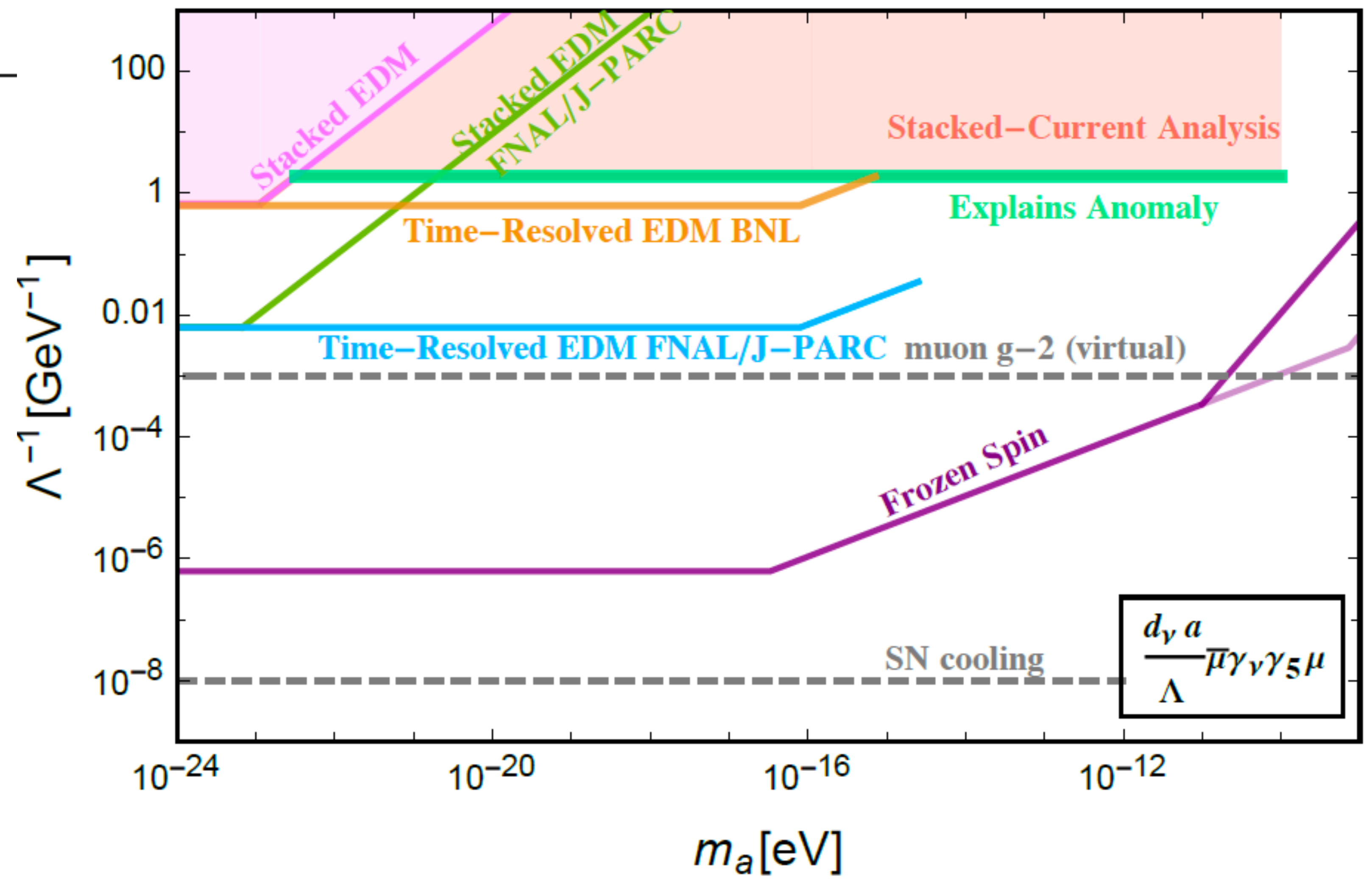
PHYSICAL REVIEW D **103,** 055010 (2021)

Storage ring probes of dark matter and dark energy

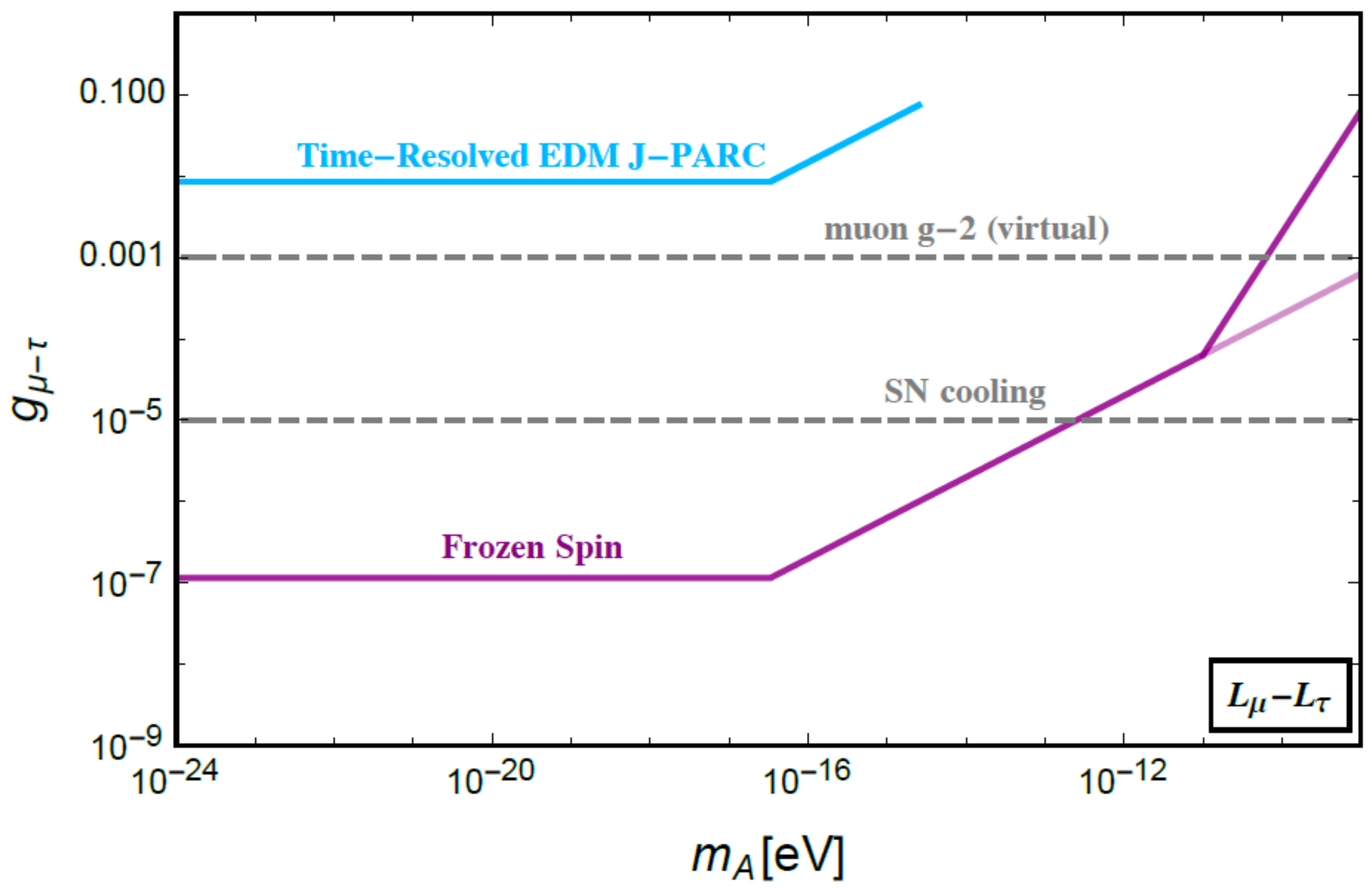
Peter W. Graham,[1] Selcuk Hacıömeroğlu,[2] David E. Kaplan,[3] Zhanibek Omarov,[4,2] Surjeet Rajendran,[3] and Yannis K. Semertzidis[2,4]

[1]*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea*
[3]*Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218, USA*
[4]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea*

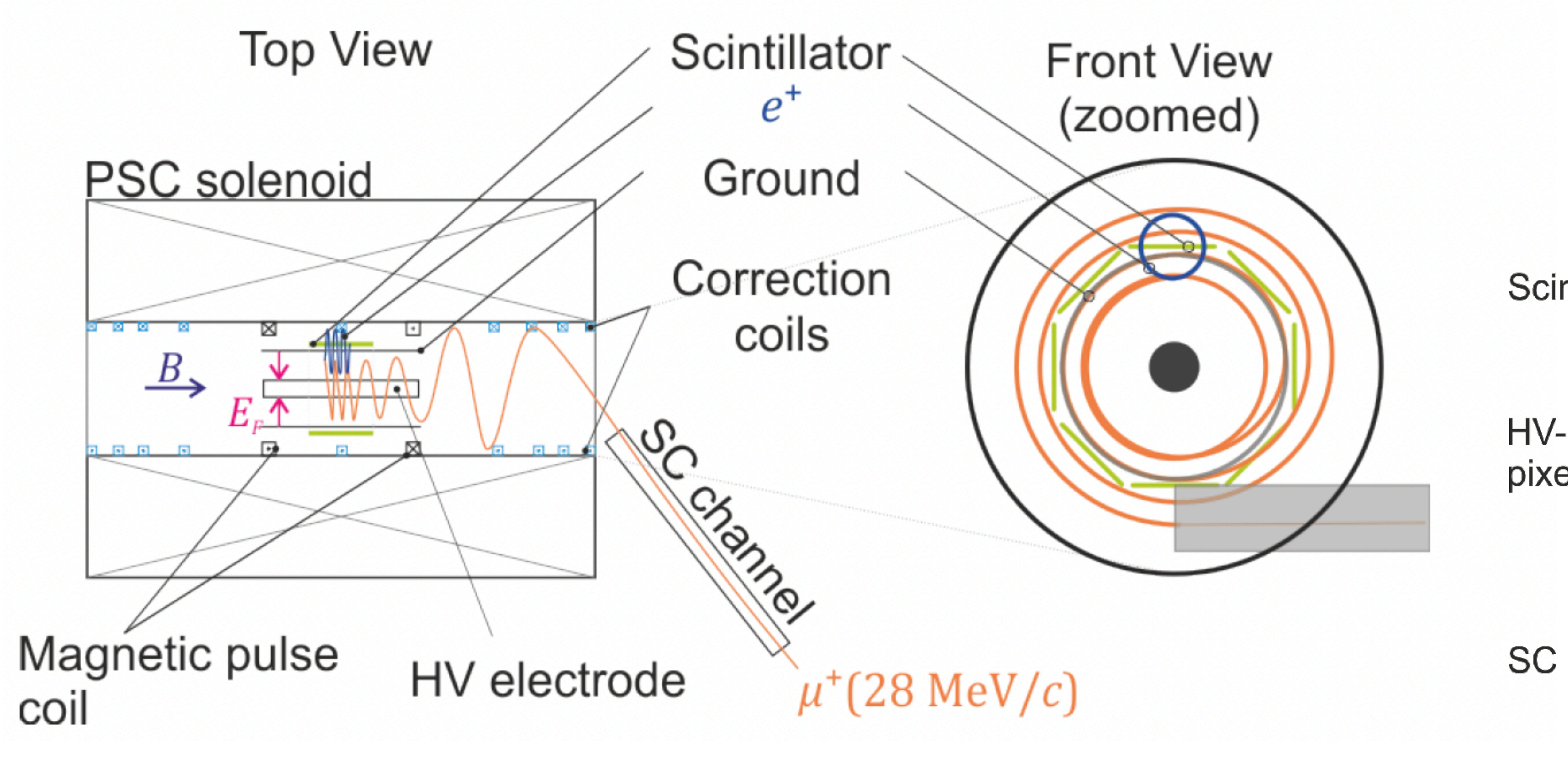
Detection Reach for ALP-Muon Wind

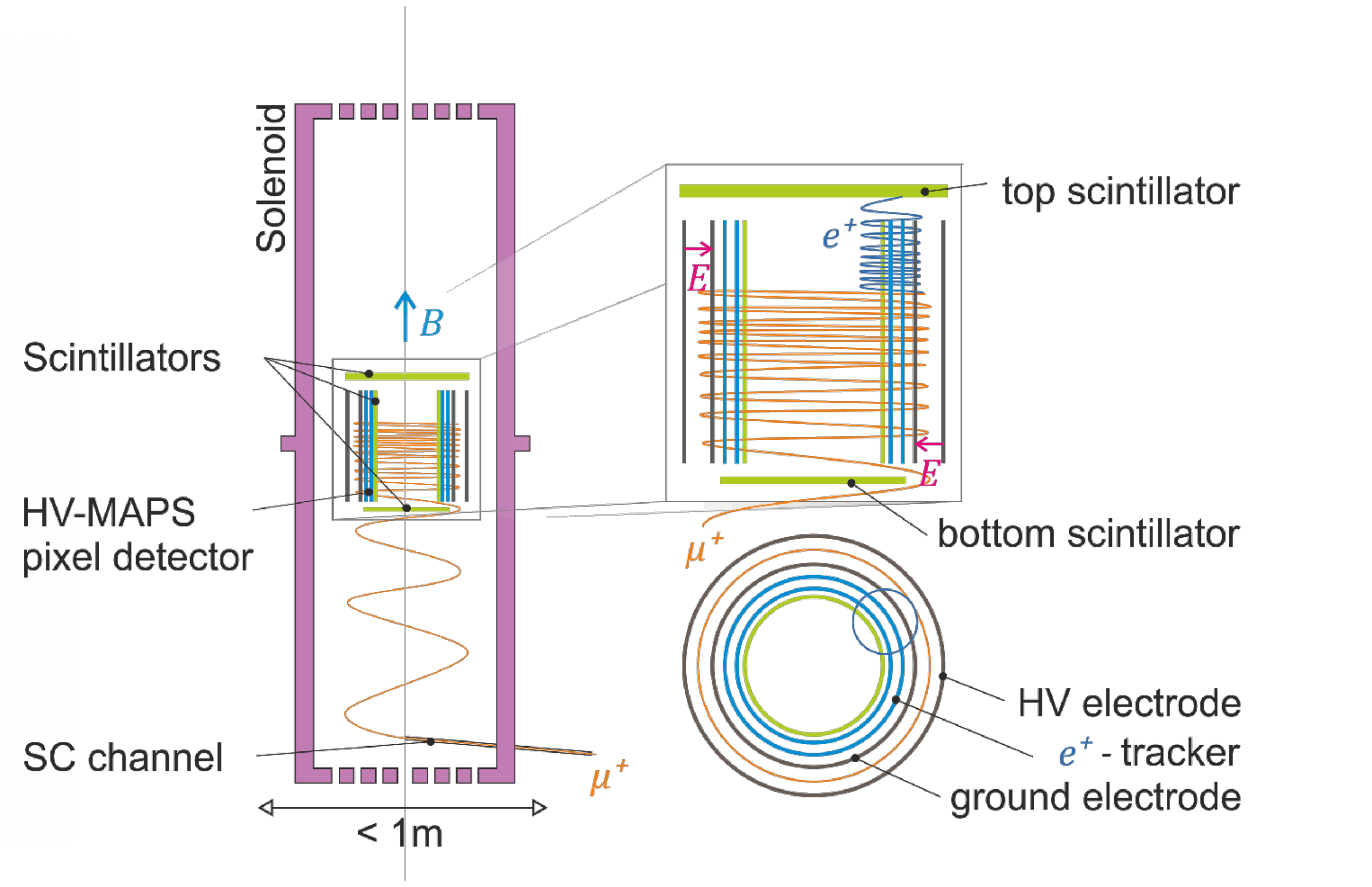


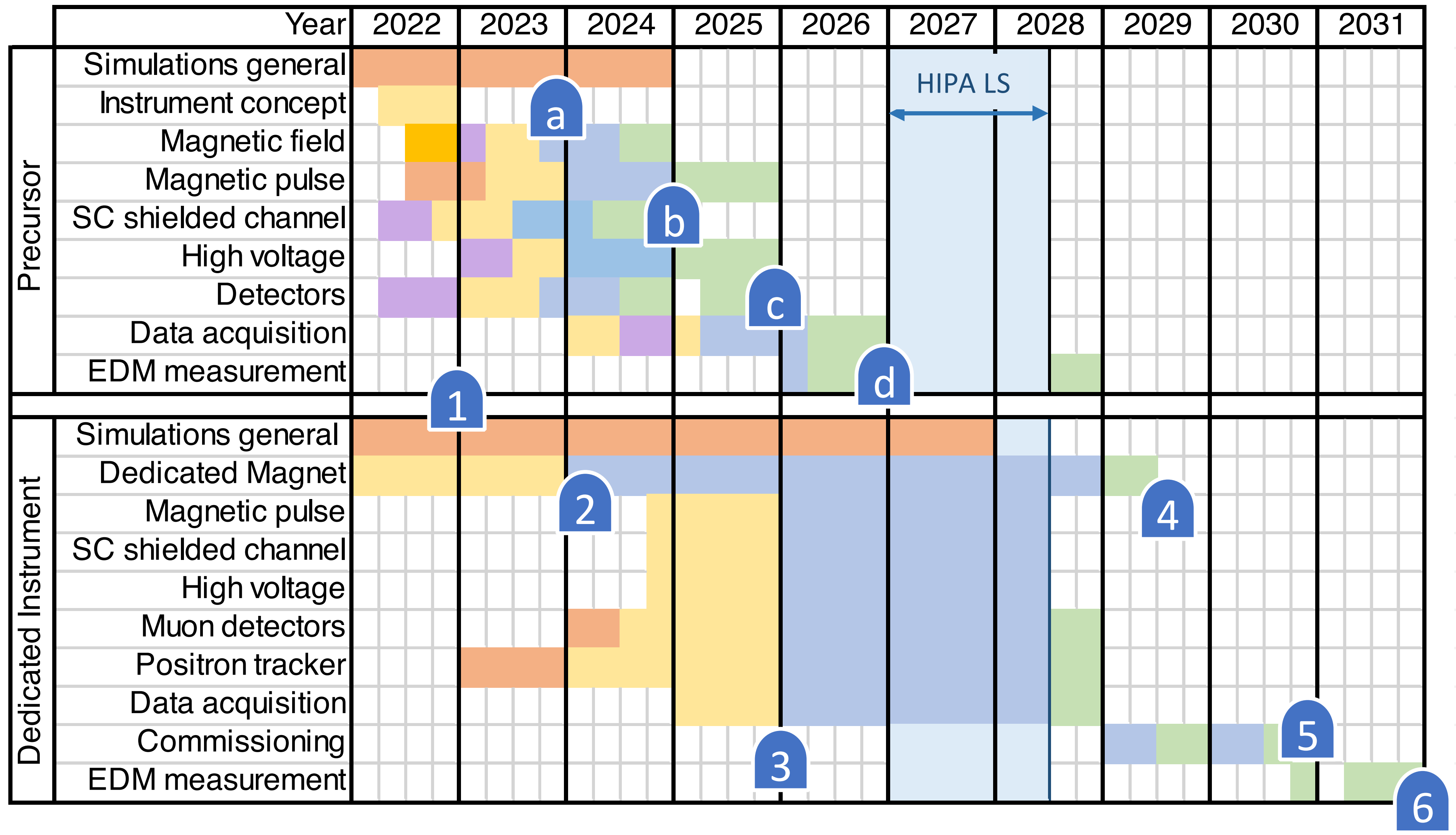
Muonic Vector DM



Summary and outlook







Phase 1 @ πE1
28 MeV/c, $d_\mu < 3 \times 10^{-21}$ e · cm

Phase 2 @ μE1
125 MeV/c, $d_\mu < 6 \times 10^{-23}$ e · cm

- Exciting time ahead as many storage ring EDM experiments (like proton/deuteron) will come online in the next few years
- Muon EDM experiments are also sensitive to muonphilic dark matter models
- We may have a better picture of the muon g-2 puzzle by then and results from EDMs will provide complementary information about muon sector BSM physics